RESEARCH AND DEVELOPMENT ON CELLS WITH BELLOW~ CONTROLLED ELECTROLY~ LEVELS

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PREPARED FOR
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FOURTH AND FINAL PROGRESS REPORT

ON

RESEARCH AND DEVELOPMENT OF CELLS
WITH
BELLOWS CONTROLLED ELECTROLYTE LEVELS

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SUMMARY

Control of electrolyte level in sealed Ni-Cd and Ag-Cd cells with bellows action has been demonstrated in 8-hour and 24-hour orbit tests over the temperature range 0°C-40°C. Bellows installed in the bottom of cell cavities collapse as cell pressures increase near the end of charge allowing electrolyte levels to fall under gravity action, exposing greater negative plate and oxygen electrode area.

Recombination rates were limited by rate and degree of electrolyte drainage from cell packs. In sealed Ni-Cd cells optimum performance was achieved with 20% KOH electrolyte and woven cloth separators. In sealed Ag-Cd cells closed "U" folds of semi-permeable membranes could not be drained. Oxygen recombination rates on exposed negative and oxygen electrodes were enhanced by drainage of electrolyte from bellows action.

A survey of metal bellows was made to locate an efficient design. A stack of rectangular plastic film pillows proved to be more efficient in weight, volume, and volume change per unit volume.

Optimum designs were incorporated in 8-A.H. and 100-A.H. Ag-Cd sealed cells for deliverable hardware. The 100-A.H. cell contains a special metal bellows with an internal normally closed switch actuated by high cell pressure to terminate charge.

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1. INTRODUCTION AND SCOPE

The Electric Storage Battery Company, Exide Missile and Electronics Division, Raleigh, North Carolina, was awarded a contract 10 June 1964 by the National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, to investigate the feasibility of controlling electrolyte levels in cycling sealed Cd/KOH/NiOOH, Cd/KOH/AgO, and Zn/KOH/AgO cells with a bellows assembly installed in each cell. The purpose of an automatic electrolyte level control device in each cell is to create a desirably high electrolyte level for discharge and a starved electrolyte level for overcharge to maximize both discharge capacity and overcharge gas recombination rates.

The contract (1) specified the following feasibility investigations:

- Task 1 - Bellows Controlled Electrolyte in Sealed Ni-Cd Cells
- Task 2- Bellows Controlled Electrolyte in Sealed Ag-Cd and Ag-Zn Cells
- Task 3- Charge Cutoff Switch Actuated by a Bellows within a Ag-Cd or Ni-Cd Sealed Cell
- Task 4- Production of Sealed Ag-Cd Cells Incorporating an Optimized Bellows Design

2. LITERATURE SURVEY

U. S. Patent 2,131,592 (2) of Lange, Langguth, Breuning, and Dassler describes the basic idea for an expansion chamber in lead acid and in nickel-cadmium batteries which allows accumulating gas to lower electrolyte levels and accelerate recombination of gases in sealed cells on open-circuit charged stand. Various types of expansion chambers are described: (a) air compartments adjacent to or surrounding the principal cell cavity; (b) a sealed bellows within an air compartment; (c) a piston actuated by a spring and trapped air; and, (d) an air compartment containing a closed cell rubber sponge. Each system is dependent upon an upright orientation during operation, a gravity force field, and requires venting to atmosphere during charge to restore the original one atmosphere condition.

U. S. Patent 2,614,138 (3) of P. A. C. Jacquier provides gas chambers reached by diffusion of gases through a porous cathode barrier.

U. S. Patent 3,208,884 (4) awarded to D. C. Jensen September 28, 1965, describes a combination pressure relief valve and compressible tube designed to compensate for compression of electrolyte into lead acid battery plates at very high water pressures when batteries equipped with the device are submerged in the ocean at great depths.

No application of the bellows in a permanently sealed cell was found in the literature.

3. SURVEY OF COMMERCIAL BELLOWS

Eleven commercial firms in the United States advertising the availability of metal and plastic bellows were contacted for engineering information. Calculations of the volume V required to install such bellows in 6 A.H. sealed Ni-Cd cells soon revealed that V might exceed the normal volume of the cell unless exceptionally efficient bellows nesting designs could be obtained.

Assuming a bellows volume change $-\Delta V$(fully extended volume less fully nested volume) of 20 cc for a cell internal pressure change of $+\Delta P$ (maximum pressure in overcharge less minimum pressure during or after discharge), characteristic values of $\Delta V/V$ were calculated for the optimum bellows designs.

Table I summarizes the physical characteristics of the bellows and lists the calculated $\Delta V/V$ performance factors. The best range of $\Delta V/V$ for commercially available bellows was 0.3 to 0.4. On a 6.0 A.H. Ni-Cd test cell of 127 cc volume, a bellows volume of 50-67 cc (40-53%) would have to be added to incorporate a metal bellows providing a control ΔV of 20 cc. Moreover, rectangular metal bellows for prismatic cell cases were not available. Stresses encountered at corners of rectangular bellows reduce cycle life and bellows seal reliability.

Preliminary tests were, therefore made to develop plastic bellows substitutes. Ultimately a series of square pillows partially inflated and then heat sealed were made from sheet polyethylene or polypropylene.

Figure 1 shows sketches of possible methods of incorporation of bellows and substitutes in cells. Note that all designs are position and gravity dependent.

4. TASK I - FEASIBILITY OF BELLOWS CONTROLLED ELECTROLYTE LEVEL IN SEALED Ni-Cd CELLS

4.1 <u>Preliminary Cell Tests</u> - As a preliminary test a 4.0 A.H. Ni-Cd sealed cell was equipped with two pillows as a more efficient substitute for a metal bellows. The two pillows were fabricated from heat sealed 4.0 mil polyethylene sheet so that under an absolute pressure change from 0.33 atm to 4.4 atm the cell pack would change from a welldrained to a flooded condition.

The fully compressed pillow volume was 4-6 cc and the fully expanded volume was 23 cc giving a calculated $\Delta V/V$ of 0.74, approximately twice the volume efficiency of the best metal bellows found during the survey.

Table II summarizes the variation in cell electrolyte level with cell pressure controlled by an outside vacuum pump or air pressure source and shows the effect of initial electrolyte volume. Electrolyte drainage kept pace with pressure changes when a single layer of 116 x 116 mesh nylon cloth was used as the interplate separator.

Table III shows the variation in electrolyte level in a similar 4A.H. sealed cell during charge, stand on open-circit, and on overcharge.

For this cell which had twice as much nylon separator thickness, drainage did not keep pace with increasing pressure. Plates remained wet and recombination was slow. However, <u>feasibility of pillow-controlled electrolyte levels was confirmed for long duration orbits</u>.

An improvement in gas recombination was needed to even test the bellows device in a 90-minute orbit cycle. Thomas[5] analyzed oxygen consumption rates on open-circuit and found that pressure decay is governed by the expression:

$$\ln \frac{P_o}{P} = \frac{RT\ ASD}{V\delta} \cdot t$$

where R is the gas constant, T the absolute temperature, A the effective negative plate surface area available for O_2 consumption, S the solubility of O_2 in the cell electrolyte at one atmosphere O_2 partial pressure, D the diffusion coefficient, V the gas volume in the cell, δ the effective thickness of the diffusion layer, and t the time elapsed between the initial high pressure P_o and the final pressure P.

To improve recombination rates the above expression predicts success for four approaches:

a. Increase negative plate area A available for recombination.

b. Increase the solubility of O_2 in electrolyte by decreasing the concentration of KOH.

c. Decrease the volume of O_2 in the cell by decreasing the free space around and above the cell pack.

d. Decrease the effective thickness of the layer of electrolyte on the negative plate.

A hundredfold increase in recombination rate was needed. Decreasing the KOH concentration from 31% to 25% would approximately double the O_2 solubility and the recombination rate. A major change in electrolyte content per cell and a rapid draining separator material appeared to be the most promising design combination.

4.1.1 Effect of Electrolyte Concentration. - Four A.H. sintered plate Ni-Cd cells were constructed in Lucite jars fitted with a detachable bellows (or pillow) chamber below the element assembly. Each jar was equipped with a needle valve and a pressure-vacuum gauge. Four polyethylene pillows served as the bellows electrolyte control device. The separator was a double layer of 4 mil, 120 mesh nylon monofilament cloth. Each cell was activated with electrolyte to give 10% plate immersion at 28 inch Hg vacuum. The variable was electrolyte KOH concentration.

During 24-hour orbit and 2-hour orbit tests the following pressure ranges were observed:

Concentration KOH (%)	24-Hr. Orbit (22/2) Pressures		2-Hr. Orbit (90/30) Pressures	
	Min.	Max.	Min.	Max.
31	5.5	23.0	-	-
25	4.1	17.6	9.9	16.8
20	1.9	14.7	6.7	14.3

Test Conditions:		
Number of Cycles	5-11	11
Charge Rate (Amps.)	0.25	2.05
Charge Input	1.37C	0.77C
Discharge Rate(Amps.)	1.40	5.6
Discharge Output	0.70C	0.70C

Pressure maxima shifted from the end of charge on the 24-hour orbit to the first 17% of the discharge on the 2-hour orbit. Pressure minima shifted from the first 10% of the charge to 33% of the charge. Figure 2 shows typical data from 24-hour orbit cycles.

The 2-hour orbit test was repeated for 20% and 25% KOH with the initial electrolyte level at 28 inch Hg vacuum increased from 10% to 70% plate immersion.

Thirty-seven continuous cycles were completed at 25°C. Figure 3 shows typical data. Pressures increased in early cycles stabilizing at about the 10th cycle. Initial electrolyte levels of 70% of plate immersion dropped to 10% plate immersion and remained at or below this level for the entire cycling period.

In all tests 20% KOH gave lower pressures than 25 or 31% electrolyte confirming previous predictions. The plastic pillows, however, developed leaks as shown by a failure to restore 70% plate immersion at 28 inch Hg vacuum, pointing to a need for more reliable seals. Also, a lag in drainage of electrolyte from cell packs was apparent in the tests suggesting that separator netting was not optimized for drainage rates.

4.2 Evaluation of Rapid Draining Separators. A bellows-controlled electrolyte level presents a new set of Ni-Cd separator requirements. Under gravity controlled conditions a rapid draining netting allows rapid bellows response, but extreme draining would cause a decrease in capacity. Table IV lists physical characteristics, including drainage from a standardized cell pack, of nine materials including very fine mesh Teflon screen at one extreme, open mesh Vexar and Nalle netting at the other extreme, two nylon monofilament cloths (120 and 96 mesh), and four intermediate grades of Teflon screen. A prediction was made from this data that cell tests utilizing selected nettings listed on Table IV might reveal an optimum choice.

Two Ni-Cd cells were manufactured and used as the netting test vehicle. Each was cycled in the open condition as follows:

a. Charge flooded cell in all cycles for 16 hours at C/10.

b. Stand on open-circuit for 4 hours.

c. Discharge at C/2 (2 amps) to 1.00 volt per cell:

Cycle No. 1	Flooded
Cycle No. 2	50% Flooded
Cycle No. 3	10% Flooded

Each separator was tested in 20% and 25% KOH electrolyte. Table V summarizes the discharge capacities observed during the open cell tests. A distinct decrease in discharge capacity was observed with decrease in % immersion for both KOH concentrations with best capacity maintenance exhibited by AGB 8-mil nylon cloth and worst by the open Du Pont Vexar 23-mil netting.

At the end of each 3-cycle discharge test in the open condition, the cells were flooded, discharged to zero volts at the C/5 rate and continued into reverse charge to prepare the negative plates for sealed cell operation. After a 4 to 5-hour open-circuit stand, the cells were drained to 10% plate immersion, evacuated to 28 inches of Hg and sealed. A single 4-mil polythylene pillow 1-7/8 x 2 inches with 1.5 cc trapped air served as a bellows device which completely flooded the plates at 28 inches of Hg. In this condition each cell was charged fully at C/10 (400 ma) and then overcharged at C/20 (200 ma).

Table V lists charge and overcharge inputs. Figures 4 and 5 give charge and overcharge voltages, cell pressures, and electrolyte levels. Only AGB 96 mesh nylon cloth was capable of extended overcharge at the C/20 rate followed by more overcharge at the C/10 rate.

On the basis of cell test data and drainage test data shown in Table IV, 67 mesh Teflon screen, type AGB 9-60-250, was selected as having optimum discharge-overcharge capability. Its 9.8 mil aperture and 10 mil thickness formed a thin film of electrolyte easily broken by overcharge gassing but quickly restored by bellows flooding action. Chemical inertness and heat stability are definite assets for Teflon while cost is the chief disadvantage.

4.3 Development of Improved Bellows.-

4.3.1 Metal Bellows. Detailed inquiries were sent to eight manufacturers of bellows with requirements for a 1.0 inch outside diameter and a ΔV volume range of 2, 4, 10, and 20 cc. Five responses yielded one bellows offering the following advantages:

a. A reasonable price including the specified end fittings with a pure nickel bellows.

b. The least extended bellows length.

c. The least compressed bellows length.

d. A competitive value of $\Delta V/V$.

e. An electroforming technique applicable to rectangular bellows.

An order was placed for ten bellows: five of the 20 cc and five of the 10 cc range.

4.3.2 Bellows Substitutes (Plastic Pillows).- A study of nonmetallic bellows substitutes in the form of plastic pillows included a survey of 20 sources of film, tubing, and bags. Appendix A lists the more promising sources and shows a typical sealing tool.

Techniques of heat sealing include hot rolling, hot pressing, and flame. Partial inflation was controlled at first by injecting air with a hypodermic needle and then resealing the puncture.

An accelerated flexure test set was developed to automatically inflate and deflate pillows at a rate once each 12 seconds. Table VI lists flexing cycle life of 12 materials which permitted a goal of 10,000 cycles in the temperature range 0°C-50°C to be set as a contract objective.

Of all the plastic films tested a 4-mil polypropylene film, Olefane A-25, Avisun Corporation, Philadelphia, Pennsylvania, displayed the best combination of properties for use in bellows substitutes. The material exhibited excellent cycle life, KOH resistance, heat seal capability, and a high value of $\Delta V/V$ volume change efficiency.

One batch of 11 pillows stacked in series, each having 0.13 inch wide seals, ran 10,600 cycles without failure immersed in KOH at 25°C. In a batch of 31 pillows, each having a 0.060 inch wide seal, 7700 cycles were completed to first pillow failure. The remaining 30 ran 14,800 cycles without failure.

To determine the effect of temperature, a batch of 11 pillows was given flex tests immersed in KOH at 0°C, 25°C, and 40°C giving 7800 thirty-five-second cycles at 0°C, 7700 fifteen-second cycles at 25°C, and 11,000 ten-second cycles at 40°C, or a total of 26,500 cycles without failure.

A calibration technique for the bellows substitute was devised to control inflation and to proof test the seals of a series of pillows stacked side by side. The bellows chamber in the Ni-Cd test cells was a cylinder with an inside diameter of 1.25 inches. A pillow diameter of 1.13 inches utilized the space available without binding during flexure. A 0.13 inch wide heat seal was later reduced to 0.06 inch as seal reliability was improved. Accurate addition of a metered volume of air was accomplished by sealing a small crushable pill of expanded polystyrene foam cut to exact dimensions inside each pillow. The diameter and height of the pill assured a reproducible volume of trapped air from pillow-to-pillow, and after being crushed left room for normal pillow flexing.

Curves of expansion volume under vacuum and compression volume under pressure were obtained for initial wall spacing (pill heights) of 0.050 inch, 0.060 inch, and 0.070 inch using 22 pillows, all of the same spacing, in a test chamber filled with water and calibrated to measure volume changes to 0.5 cc accuracy. Figure 6 shows compression and expansion curves for the 22-unit polypropylen-pillows.

Total volume change approaches a maximum value in the .05 - .07 inch range of wall spacing in the imposed pressure range of 2 - 75 psia:

Wall Spacing (in)	Compression (ΔV,cc)	Expansion (ΔV,cc)	Total (ΔV,cc)
0.050	4.0	16.0	20.0
0.060	5.0	22.0	27.0
0.070	7.0	21.0	28.0

Using the same test chamber and technique, calibration tests were run at 25°C on the 10-cc and 20-cc nickel bellows and for comparison on six different numbers of polypropylene pillows (25,30,35, 40,45, and 50 units). Figure 7 shows the change in volume of pillows in expansion and compression as a function of the number of units. Figure 8 compares the action of 10-cc and 20-cc nickel bellows with a 35-unit polypropylene bellows substitute. Several points are clear:

a. Each calibration curve has two arms representing volume change: one for compression and one for expansion.

b. Both metal bellows divide their rated capacity equally between expansion below 15 psia and compression above 15 psia. Each has a maximum limit beyond which cycle life is reduced: 35 psia for the 20-cc bellows, and 25 psia for the 10-cc bellows.

c. The number of pillow units in the polypropylene bellows assembly affects the division of volume change between expansion and contraction as can be seen in the data summary below read from Figure 7:

Number of Pillows	Volume Change Between 5 and 75 PSIA				
	Compression		Expansion		Total
(Units)	(cc)	(%)	(cc)	(%)	(cc)
25	6.0	37	10.6	63	16.6
30	7.5	38	12.4	62	19.9
35	9.0	42	12.6	58	21.6
40	10.2	45	12.4	55	22.6
45	12.5	55	10.2	45	22.7
50	14.5	64	8.1	36	22.6

A 42-unit pillow assembly would thus act almost equally between compression and expansion in the pressure range 5 to 75 psia. This characteristic of pillow assemblies offers the possibility of a bellows "tailored" to the job.

d. Operating temperature extremes changes the performance of polypropylene pillows adversely, but the effect is small in the temperature range 0-40°C:

Operating Temperature (oC)	Volume Change Between 5 and 75 PSIA Compression (cc)	Expansion (cc)	Total (cc)
0	9.0	9.4	18.4
25	9.0	12.7	21.7
40	9.5	11.5	21.0

e. In summary, a capability of producing "tailored" pillow-type plastic bellows substitutes has been developed using inexpensive, easily obtainable materials. Life equivalent to one year of 90-minute cycling orbits may be reasonably expected.

4.4 Evaluation of Six Ampere-Hour Sealed Ni-Cd Cells With Bellows Electrolyte Level Control. - In order to optimize discharge and overcharge capability in sealed Ni-Cd cells having bellows-controlled electrolyte levels 15 six ampere-hour cells were manufactured. These cells contained five separator systems, four types of bellows, and two electrolyte levels as evaluation parameters. Table VII summarizes the design factors selected on the basis of preliminary cell tests. The three rapid draining cloths and screens contrast the performance of the non-draining Pormax control separator. Monofilaments wrapped around the negative plates increased drainage rates without impairing discharge or overcharge performance. The 20-cc and 10-cc metal bellows permitted a comparison with the more efficient 40 and 50-pillow plastic assemblies. ESB noble metal oxygen electrodes 0.63 inch x 3.25 inch x 0.015 inch were placed in all cells except S/N12, 13, and 14 to enhance 0_2 recombination. Previous data from sealed 4 A.H. Ni-Cd cells cycled on 24-hour orbits split 22/2 showed lower pressures and higher electrolyte levels throughout testing as summarized below:

Cycle Period	Electrolyte Level Variation in % Plate Immersion Without 0_2 Electrode	With 0_2 Electrode
During pressure build-up at end of charge	42 to 18	100 to 46
Pressure decline during discharge	18 to 23	46 to 74
Pressure decline during early charge	23 to 28	74 to 94

All other design factors common to all cells were selected as the result of preliminary cell screening tests.

Table VIII summarizes the test plan for the 15 cells. A review of screening test data led to changing the proposed 2.0-hour orbits to 8.0-hour orbits to improve the feasibility of unattended operation of the bellows cells. All cells were given a series of tests to establish the limitations of electrolyte level control by bellows and pillows:

- 20-cc nickel bellows gave complete flooding and draining at reasonable cell pressures for all separator types.
- 10-cc nickel bellows could drain only one separator (Type "B") without being compressed beyond the manufacturer's recommended limit.
- At least 40 pillows per assembly were needed to give complete flooding and draining for all separator types.

Discharge tests were then run at rates of C/5, C/2, and C/1 at electrolyte levels of 100, 50, and 10% plate immersion. Typical cell discharge performance for the separator systems Pormax, Teflon screen, and Teflon plus nylon is plotted in Figures 9, 10, and 11. A capacity drop with reduced electrolyte level was observed at each discharge rate for all separators.

Prior to sealing, all cells were discharged flooded and reverse charged to establish a ratio of charged negative to charged positive plate capacity of 1.35 minimum. Cells 4, 8, and 9 were sealed with no bellows in the forced drain condition. Cells 1, 2, and 3 with nylon-Teflon separator and cells 5, 6, and 7 with Teflon screen only as a separator were sealed with bellows and under a partial vacuum to give an initial electrolyte level of 87 to 100% plate immersion. Table IX gives the observed cell conditions at varying stages of overcharge testing. Of the control cells only cell S/N 9 containing Pormax could overcharge successfully. Bellows action for both metal bellows and the 31-unit pillow assembly was synchronous with pressure variation. A combination of nylon and Teflon appeared to offer the best overcharge characteristics, running 24 hours at C/10 and 4 hours at C/5 overcharge rate.

As a result of the above baseline tests, cells 4 and 8 were equipped with 50-pillow units and cells 3 and 7 were modified increasing the number of pillows from 31 to 40 each prior to beginning cycle tests.

4.5 Proof Cycling, Extreme Temperature, and Final Cycling Tests. - The evaluation program given in Table VIII was carried to completion involving 15 test cells S/N 1-15. Cells S/N 1 through 9 completed 85 room temperature cycles: 30 on a 24-hour orbit, 42 on an 8-hour, and 13 on a 2-hour orbit regime. Cells 10 through 15 were cycled at the temperature extremes of 0°C and 40°C on 24-hour and 8-hour orbits. The results of this test program may be seen in Figures 12 through 23. The principle observations given below were obtained from working plots of cell voltage, cell pressure, and electrolyte level (in % immersion with 100% meaning flooded to top of plates) prepared for each experiment.

4.5.1 Effect of O_2 Recombination Electrodes.- Overcharge tests at C/20, C/10, and C/5 on cells with and without ESB O_2 electrodes showed that cells with O_2 electrodes ran at consistently lower pressures. A close competitor was a cell design with no O_2 electrodes but having negative plates wrapped vertically with 11-mil monofilament strands to aid in electrolyte drainage. Rate of pressure loss on open circuit was greater with O_2 electrodes. Equilibrium pressures were lower with O_2 electrodes. Bellows action restored flooded conditions desired for the next discharge more rapidly with O_2 electrodes than without. Equilibrium electrolyte levels were the same. Figure 12 shows a portion of the data for cells with 10 cc and 20 cc nickel bellows, and 40 pillow units.

Figure 13 shows the action of 20-cc metal bellows and the 40-pillow unit bellows at 0°C and 40°C with and without O_2 electrodes while cycling on a 22/2-hour orbit. Pressures are considerably higher without O_2 electrodes. Monofilaments on the negatives also enhance the operation of the 20-cc metal bellows at 0°C.

4.5.2 Effect of Fill Level. - Figure 14 shows the effect of initial fill level on working cell pressure and bellows action. Lower fill levels, such as 33% and 50% plate immersion at 1 atmosphere, give lower cell pressures allowing bellows action to maintain higher electrolyte levels throughout 22/2-orbit cycling at 25°C.

4.5.3 Effect of Bellows and Separator Type. - Figure 15 shows electrolyte level and cell pressure control by 10 and 20-cc nickel metal bellows and by 40 and 50-pillow unit bellows substitutes for separator systems "A" and "D". A control cell with Pormax separator and no bellows contrasts conventional cell performance. At 11 hours of charge at the C/6 rate, exactly midway in the charge portion of the orbit the following comparisons can be made:

Bellows Type	Separator "A" Electrolyte Level %	Separator "A" Cell Pressure psia	Separator "D" Electrolyte Level %	Separator "D" Cell Pressure psia
Nickel Metal:				
10 cc	40	30	40	75
20 cc	40	32	10	35
Polypropylene Pillows:				
40 unit	40	28	25	35
50 unit	25	25	23	53
Averages	38	29	25	50

Pormax gave 75 psia at 11 hours of charge. Thus, separator system "A" maintained low cell pressures and high electrolyte levels. The cell with the 10-cc metal bellows was little better than the control cell with no bellows at all. The 20-cc metal bellows and the 40-unit pillow assembly give excellent electrolyte level control.

Figure 16 verifies that bellows containing cells give 19 per cent greater capacity at the C/3.6 rate to 1.20 volt per cell.

4.5.4 Effect of Temperature on Bellows Operation. - No significant variation in comparable nickel bellows and polypropylene pillow assemblies was noted at 40°C. At 0°C a tendency was seen for expansion of the plastic pillows to be inhibited by the decreased flexibility of polypropylene. Figure 17 shows this effect at 0°C at two charge rates: C/20 and C/10 amps.

4.5.5 Bellows Operation on 8 Hour Orbit Tests. - The sealed Ni-Cd, 6 A.H. cells were also tested on a cycle consisting of charge for 7 hours at C/5 followed by discharge for 1 hour at 4.2 amperes (0.7 C rate) at 0, 25 and 40°C.

Figure 18 shows the superiority of the 20-cc metal bellows and the 45-pillow unit over the other bellows types, but shows that the cell pressure is similar to the control cell without any bellows. Figure 19 gives the discharge voltage characteristics of the same cells at the 0.7 C rate at 25°C. Cells containing separator type "A" (1 L 10 mil Teflon screen) and either a 20-cc metal bellows or 40 polypropylene pillows give 10 - 15 % longer run time to 1.05 volts per cell test end voltage. The control cell with no bellows is superior to the 10-cc nickel and 50-pillow bellows in this test.

At a test temperature of 0°C both 20-cc nickel bellows and polypropylene pillow exhibited sluggish action with little change in electrolyte level during the 8-hour cycle. The data is shown in Figure 20. It may be concluded that with 20% KOH and all four types of separators bellows action is not feasible at 0°C on an 8-hour orbit test.

At a test temperature of 40°C, bellows action is feasible on the 7/1 type orbit as is shown in Figure 21. Even at 40°C, however, gas can be trapped within the cell pack making bellows operation and electrolyte level quite variable from cycle to cycle.

4.5.6 Bellows Operation on 2 Hour Orbit Tests. - Cells S/N 1,2,3, and 4 with separator type "D" were cycled on the 2-hour orbit test of 90 minutes charge at C/1.9, followed by 30 minutes discharge at 1.4C. Figure 22 shows excellent bellows response with maximum electrolyte levels matching minimum pressure periods at 30 minutes of charge and high pressure periods coinciding with end of charge.

Figure 23 gives the discharge voltage characteristics of the same cells discharging at 8.5 amps (1.4C) for 30 minutes at 25°C. No significant differences in voltages were observed between the control cell with no bellows and the best of the bellows tested: 20-cc nickel and 40-pillow polypropylene unit.

4.6 Conclusions for Task 1. - Based on the test program results, the following conclusions can be made regarding construction features of the sealed Ni-Cd cells with bellows controlled electrolyte level:

4.6.1 Separators. -

a. Good oxygen recombination was obtained with all four separator types. The highest recombination rate was shown by Type "A" (1 layer, 10 mil, AGB 9-60-250 Teflon screen), but its relatively large openings are considered inadequate for protection against short circuiting due to floating particles.

b. Type "B" (2 layers, 4 mil, AGB-8M nylon cloth) offered the greatest economy of electrolyte. By producing a compact plate pack, the volume of electrolyte to completely flood is kept at a minimum. The cell volume reserved for bellows, therefore, would be reduced to a minimum. The main disadvantages of type "B" lie in the combinaton of small interplate distance, microscopic openings, and lack of rigidity inviting shorts by plate irregularities (grid wire ends, bent corners, bent plates at the lug, surface eruption or blisters).

c. Type "C" (type "B" plus vertical strands of 11-mil monofilament nylon) increased the interplate spacing and generally overcame the shorting problem of type "B" at the expense of manufacturing difficulty in applying filaments in regular order and in fastening the free ends.

d. Type "D" (one layer, 120 mesh 4-mil nylon cloth plus one layer 67 mesh 10-mil Teflon screen) provided a barrier against floating particles and adequate interplate spacing.

4.6.2 Electrolyte Fill Level and Sealing Condition. - The strong wicking properties of impregnated, sintered nickel plaques assures a supply of electrolyte to the top of a 6-inch plate just dipping into a reservoir of KOH solution. With a relatively low level of fill (30% immersion), a bellows equipped cell can be sealed in the flooded condition by evacuation.

4.6.3 Oxygen Electrode. - The enhancement of recombination rate by auxiliary reaction sites is considered an essential parameter for a successful bellows controlled sealed cell.

Further utilization of the void space above the plate pack for additional oxygen electode area is recommended. A sheet of oxygen electrode material could be attached to each negative plate along its upper edge within the plane of the plate.

4.6.4 Bellows. - The use of individual pillow type bellows made from Avisun 4-mil polypropylene is recommended. An internal wall spacing of 0.070 inch was found to be the maximum value for heat sealing reliably rectangular pillows, 7/8 inch by 1 1/8 inch. A grouping factor of 15 pillows per inch of chamber length gave bellows action almost equally divided between compression and expansion.

5. TASK 2 - FEASIBILITY OF BELLOWS CONTROLLED ELECTROLYTE IN SEALED Ag-Cd CELLS AND SEALED Ag-Zn CELLS

5.1 Introduction - In contrast to the cell system Cd/KOH/NiOOH, which needs only an absorbent non-woven interplate separator, cells based on the systems Cd/KOH/AgO or Zn/KOH/AgO require a semi-permeable membrane separator system with mean pore diameters 10-15 Å to stop the diffusion of suspensions or solutions of positive plate oxidant toward the opposing negative plates. In cells containing zinc anodes and to a lesser degree in cells containing cadmium anodes the semi-permeable membrane must also prevent the growth of conductive zinc metal dendrites or cadmium metal moss between plates. Omission of a semi-permeable membrane in either of the two cell systems will result in metallic interplate shorts within the first few charge-discharge cycles.

A semi-permeable membrane between cycling positive and negative plates in the silver systems also creates by osmotic effects a rise and fall of electrolyte level. Individual electrode reactions consume or produce $O\bar{H}$ ions. The change in concentration of $O\bar{H}$ ions in anode and cathode compartments and the resulting changes in electrolyte levels are given in Table X.

The degree of level change is dependent upon charge time, capacity, and the membrane diffusion coefficient. Level changes were observed in 50 A.H. sealed Ag-Zn cells with multi-layer cellulosic membranes wrapped in "U" fold array on the positive plates. At the completion of a 164-hour modified CP float charge, a pronounced membrane electrolyte level effect was detected[6] as follows:

Membrane		Wet Thickness mils	Increase In Electrolyte Level Around Exposed Negatives, In.				Level Increase In/mil
No. Layers	Type		Cell 1	Cell 2	Cell 3	$\bar{x}$ n=3	
5	193 Pudo	16.5	1.70	1.41	1.35	1.49	.090
6	193 Pudo	19.8	1.65	2.50	1.88	2.01	.101
1 5	Permion 300 193 Pudo	17.5	1.75	2.05	1.70	1.83	.105
1 6	Permion 300 193 Pudo	20.8	1.60	1.65	1.50	1.58	.076
2	Fibrous Sausage Casing	15.5	0.30	0.25	0.25	0.27	.017

Cellophane would appear from this data to be 3-5 times less capable of passing electrolyte than fibrous sausage casing.

Correspondingly, in the negative compartment the electrolyte level falls during discharge. In an orbit providing equal charge and discharge capacities but with <u>greater</u> charge times, Ag-Zn and Ag-Cd cells with cellophane type membranes will rapidly become electrolyte limited in the positive plate compartment. Water will flow predominantly from the water-rich positive to the negative compartment decreasing positive plate electrolyte levels and increasing (OH-) to a capacity limiting point during charge.

A bellows device can not aid in the solution of this problem unless bellows action can pump electrolyte from the compartment with a high level to the one with the lower level. Engineering such a device was considered beyond the scope of this contract.

It was decided that the feasibility study would be directed at a bellows design which could promote gas recombination rates by lowering electrolyte levels around the negative plates during high oxygen pressure periods.

5.2 Design of Ag-Cd Test Cells. - Table XI outlines the design characteristics of the twenty-four 8 AH cells which were fabricated as shown in Figure 24.

Rather than using a metal bellows, a bellows substitute was employed. The substitute consisted of 30 individual polypropylene pillows 1.25 inch x 0.88 inch made of 4-mil Avisun stock sheet heat sealed along an outer .060 inch border. A plastic cage was constructed in the bottom of the cell jar to position the pillows for efficient operation and to provide protection from sharp plate edges. Table XI shows that the bellows cavity occupies 20.7% of the inside cell volume even with the high efficiency $\Delta V/V$ ratic of the pillows. This expenditure of space for electrolyte control is matched by a loss in cell capacity.

Each cell contained two full sized ozygen electrodes adjacent the outside negative plates, connected electrically in parallel and via a third cell terrminal through an external switch-ammeter circuit to the main cell negative terminal. The ratio of positive plate area to exposed oxygen electrode area was 3:1 (48 in^2/16 in^2) at the lowest electrolyte level(pillows fully compressed) in each cell.

Four separator systems were chosen for initial cell tests and were distributed 4 cells for each code type:

Code No.	Absorber	Semi-Permeable Membrane	Style of Wrap
1	1L polypropylene*	5L Borden C-3	"U" fold on positives
2	1L polypropylene	1L ESB RC-901B	Heat sealed bag on each positive plate
3	1L polypropylene	5L Borden C-3	"U" fold on negatives
4	1L polypropylene plus wick extension	1L ESB RC-901B	Heat sealed bag on each positive plate

(*) Kendall Mills EM 476

An electrolyte of 20% KOH was chosen initially to promote rapid drainage and solubility of oxygen in the electrolyte, striving for maximum recombination rates at a sacrifice in capacity. During the gassing phase of the formation charge, when O_2 is formed at the fully charged positives while the CdO negatives are approaching full charge, copious quantities of detergent foam poured from the cell vent of all cells containing Borden C-3 separator. Fearing partial decomposition of the C-3 membrane, the 20% electrolyte was flushed out with 40% KOH, and then replaced with fresh 31% KOH. Foaming subsided considerably but was never completely eliminated and was an unexpected complication.

The cells were equipped with 1/8 inch pipe nipples and T connections fitted with a Hoke needle valve and a dial pressure-vacuum gauge. Just prior to sealing, each cell was evacuated and back filled with pure O_2 until an amount equivalent to 1.5 A.H. of negative plate capacity had been consumed. Electrolyte levels were then adjusted so that at seal two of each four cells of each separator type had plate packs immersed 50% and two immersed 75%.

5.3 <u>Twenty-Four Hour Orbit Cycling Tests.</u> - A number of 24-hour orbit cycles (22-hour charge, 2-hour discharge) were performed at 25°C. Figure 25 presents typical cell voltages, pressures, electrolyte levels, and oxygen electrode recombination currents observed during cycling tests. Cells A-1 and A-3 with five layers of Borden C-3 "U" folds on the positives show electrolyte levels falling during the last six hours of charge when cell pressures rise, and corresponding increases in recombination current with complete restoration during the two-hour discharge. This action is considered a desirable response.

Cells C-2 and C-4 with five layers of Borden C-3 "U" folds on the negatives operate at higher pressures, show lower electrolyte levels (around the exposed positives) and higher cell voltages. Electrolyte levels decrease almost from the beginning of the charge period continuing to 5% plate immersion by the end of the 22-hour charge period. Recombination currents did peak at the end of charge but were not as high as the A-1 and A-3 cells. Figure 25 data thus suggests improved cell operation can be obtained with membrane type "U" folds on positive plates, and bellows action exposing a greater active area of oxygen electrodes at no increase in cell voltages and a decrease in cell pressures.

Figure 26 demonstrates the effect of replacing a semi-permeable, multi-layer membrane system with one layer of a thicker more permeable membrane RC-901 placed as a sealed bag over each positive plate. Cells B-2 and B-4 show a more rapid rate of level change occurring during the last 2 hours of charge. Cells D-1 and D-3 are like cells B-2 and B-4 except that an absorber wick was used to siphon electrolyte from the high level site to the low level site. Level changes occur continuously during charge and discharge, but again voltages rise with increasing drainage. Here, the only visible electrolyte level was that around the exposed negative plates. The RC-901 material was opaque, preventing observation of electrolyte level within the positive envelopes. Figure 26 data confirms wicking action but again suggests bellows action promotes a vicious cycle of raising charge voltage while improving recombination conditions slightly.

Gradually rising pressures in all eight cells indicated hydrogen evolution. The cells were therefore vented and treated with oxygen to obtain a reserve of uncharged CdO of 4.5 A.H. and then resealed. Figure 27 shows the dramatic improvement in bellows response and recombination currents in cells A-1 and A-4 where the membrane system (Borden C-3) was closed "U" folds on the positives. Both recombination current and electrolyte level almost flatten out into equilibrium overcharge conditions during the last two hours of charge and recover almost completely during the 2-hour discharge.

Cells C-2 and C-3 of Figure 27, having Borden C-3 "U" folds on the negative plates, show little bellows response and a difference in charge acceptance with initial fill level. Cell C-2, with 50% plate immersion as the initial fill level, shows lower electrolyte levels throughout, higher cell charge voltage and pressure, and higher recombination currents. This cell gave gradually decreasing capacity.

Figure 28 gives the improved bellows and oxygen electrode action resulting from the second oxygen treatment on cells D-2 and D-4 having RC-901 separator bags on each positive plate. Cell pressures never exceeded 20 psia. Electrolyte levels remained near 100% negative plate immersion out to 15 hours of charge falling by the 18th hour to a near equilibrium value as recombination currents rose in tandem to a maximum, or near maximum value on the 20th hour of charge. Again, high electrolyte levels were restored during the 2-hour discharge.

In summary, in 24-orbit cycling tests on 8-A.H. sealed Ag-Cd cells oxygen electrode response kept pace with bellows-controlled electrolyte levels maintaining cell pressures at or below 20 psia when membrane type separators were placed in "U" fold array on positive plates. Low initial electrolyte levels gave higher cell voltages and pressures. Bellows action permits higher cell electrolyte levels without higher cell pressures and does keep cell voltages in better regulation.

5.4 Cycling Tests in Eight-Hour Orbits. - Four sealed 8 A.H. Ag-Cd cells were next constructed with solid Lucite blocks in the cavity normally occupied by the bellows device and tested through eight cycles of charge at 0.7 amps with a 1.53 volt per cell voltage limit for 7 hours followed by 1.0 hour of discharge at 4.0 amps. Figure 29 lists the four separator systems tested, the initial electrolyte fill levels, and shows electrolyte level variation and oxygen electrode response on cycles 7 and 8. Relative performance may be summarized:

Cell No.	Separator System	Pressure, PSIA		Electrolyte Level,%		Recombination Current, ma Max.
		High	Low	High	Low	
A-5	5L C-3 on pos.	18	13	48	35	72
C-5	5L C-3 on neg.	13	11	44	20	18
B-5	RC 901 bag on pos.	30	27	40	23	32
D-5	B-5 plus wick	16	13	24	19	52

In all cells by the end of 8 cycles electrolyte levels had dropped from the initial 50% immersion at full vacuum to 20-40% immersion at the stabilized pressures. Most consistant oxygen electrode response was obtained in the cells with RC-901 membrane bags on the positives. The maximum fluctuation in electrolyte level was in cell C-5 with Borden C-3 "U" folds on the negatives. In all the control cells operating capacities after long term cycling would have become a function of keeping positive plates adequately wetted with electrolyte in spite of the low electrolyte levels.

Four more cells were constructed to test the repeatability of cells containing R-C 901 bag type separators on positive plates with a bellows device. Two cells were filled to the 50% level and two cells to the 75% level. A 30-pillow bellows device replaced the Lucite block in the bellows cavity.

Figure 30 shows that at the end of seven 8-hour (7/1) cycles electrolyte levels were still above the 90% immersion level at the peak level time of 3-4 hours of charge, with bellows action and oxygen electrodes maintaining low pressures. More pronounced bellows action was obtained in the cells with the highest initial electrolyte level.

In summary, sealed Ag-Cd cells can be made with bellows devices to maintain high plate immersion levels for good capacity in low pressure periods, yet promoting good oxygen electrode performance by drainage of electrolyte from around the cell pack during high pressure periods. In 8-hour cycles to 50% depth of discharge minimum electrolyte levels occur at the end of the 7-hour charge while maximum electrolyte levels occur between 3-4 hours of charge. Operation on 90-minute orbits was not successful. High pressures developed keeping bellows in a continuously compressed state.

6. TASK 3 - FEASIBILITY OF BELLOWS ACTUATED CHARGE CUT-OFF

A logical application of a metal bellows in a sealed cell is one in which the compressed bellows will actuate an electrical switch terminating the charge at a preset cell pressure. To test the feasibility of this technique, a special metal bellows was purchased from the Servometer Corporation and equipped with Klixon A T 1 - 1 switch assembly.

The switch assembly was tested after installation in the bottom of a 100 A.H. Ag-Cd sealed cell case. An actuator stud, screwed into the moving end base plate of the bellows, was varied in length until a predetermined cell pressure collapsed the bellows allowing the stud to actuate the microswitch. Operation was found to be feasible, but the reliability was dependent upon accurate tracking of the expanding and collapsing bellows and upon the seal between the collar of the stainless steel switch mount and the polystyrene jar wall where the switch lead wires protruded. A combination "O" ring epoxy seal was the best seal achieved during the contract period. Reliable tracking under ambient test conditions was achieved with a plastic cage to direct the motion of the bellows.

It was not feasible to obtain an adequate volume change and switch action with the same bellows. A combination pillow assembly and bellows-switch assembly was a compromise design which utilized space and weight more efficiently.

The design features of a 100 A.H. sealed Ag-Cd cell containing a bellows actuated charge cutoff are summarized in Table XII. A side view of the cell is given in Figure 31 to show the bellows-switch assembly and pillow cage. The Servometer bellows was 1.54 inches long by 0.95 inches in diameter and consisted of 11 omega type convolutions. The combined weight of bellows, switch, switch mount, and epoxy seal was 60 grams.

An alternate approach to terminating charge at a given pressure is to use a pressure transducer on each cell. A typical reliable pressure transducer, manufactured by Bourns, Inc., for a pressure range 0-150 psia, weights 95 grams, is 2.3 inches long by 1.0 inch in diameter, including connector and fittings, and does not contain a switch action. The voltage signal of the pressure transducer would need additional electronic circuitry to terminate charge.

The space and weight of one pressure transducer per cell can be reduced to one transducer per battery if a manifold is provided as a common venting chamber for all cells. Then change would be terminated when the manifold pressure exceeds a preset cut-off point. This approach is now being tested in space in a sealed Ag-Zn battery designed for use on a lunar probe.

An improvement upon the bellows-switch design of Figure 31 would be a miniature bellows switch built into one cell terminal with the bellows in the normal air space of a cell above the plates and the actuator shaft extending through the terminal stud into a microswitch assembly outside the cell. It would be most desirable to have the pressure cutoff adjustable after the cell is sealed. Development of such a switch was considered beyond the scope of this study.

7. TASK 4 - DELIVERABLE HARDWARE

Five cells of 6 to 12 ampere-hour capacity and five cells of 100 ampere-hour capacity were delivered to NASA demonstrating the best technique developed for controlling electrolyte levels with a bellows. The system chosen was sealed Cd/KOH/AgO.

Cells of 8 A.H. capacity, similar in general construction to Figure 24 of Task 2, were fabricated. A pillow cage, containing 30 polypropylene pillow units, was installed in the bottom one-fifth of each cell cavity to drop the cell electrolyte level from 75% plate immersion to 5% plate immersion. Each cell had two full-size oxygen recombination electrodes connected to a third terminal protruding from the cell cover seal. Oxygen recombination currents could thus be monitored at will. Each of the four positive plates was bag-wrapped with ESB RC-901Borange separator. Inside the bag a "U" fold of Kendall Mills EM 476 served as a positive plate absorber-wick to keep the positive wet and to wick electrolyte between plate compartments. Two layers of Borden C-3 were placed in open "U" fold around each bag to improve cell life. This system was chosen primarily because of its rapid drainage capability to enhance the action of the oxygen electrodes.

Each cell cover seal was provided with a 1/8 pipe vent hole to allow activation, adjustment of electrolyte level, pressure monitoring with a gauge assembly, or sealing with a pipe plug coated with Scotch white teflon pipe tape.

Figure 32 gives the formation discharge and recharge test data obtained at ESB prior to shipment of the cells to NASA.

Five 100 A.H. sealed Ag-Cd cells were fabricated as a scale-up version of the 8 A.H. cell, except for a revised positive separator system of six layers of 193-PUDO cellophane and one layer of EM 476 in closed "U" fold array. This cell was described in Task 3, Table XII and Figure 31. The combination pillow assembly of 22 pillows per cell and the Servometer bellows-switch assembly was designed to control the cell electrolyte level from a maximum of 90% plate immersion at vacuum seal to a minimum of 25% plate immersion at maximum cell operating pressure. Each of the 100 A.H. cells was equipped with a pressure gauge and valve assembly to permit adjustment of electrolyte levels, if needed, by NASA.

Figure 33 shows the formation discharge and second cycle charge monitored by ESB before shipment.

8. CONCLUSIONS AND RECOMMENDATIONS

Control of electrolyte level by bellows action in sealed Ni-Cd cells is feasible in a 24-hour orbit at 50% depth of discharge at 0, 25, and 40°C when 22 hours is allowed for recharge. On an 8-hour orbit (7/1), performance at 0°C is sluggish even with 20% KOH electrolyte. On a 2-hour orbit with 90 minutes for recharge, bellows action keeps pace with recombination rates augmented by two full-sized oxygen electrodes. At 0°C pressures build up, keeping bellows fully collapsed, even with the plate pack and oxygen electrodes in a well-drained condition.

Control of electrolyte level by bellows action in sealed Ag-Cd cells is possible external to the closed "U" folds of separator in the cell. Best performance is achieved with closed "U" folds on positives and two O_2 recombination electrodes shorted to the negative plates. Successful operation is limited to 8-hour orbits and longer times in the temperature range zero to 40°C.

Discharge voltages are maintained at higher levels during the last 20% of discharge when bellows action is successful in flooding negative plates. Cell working pressures are lower, especially when cells are equipped with oxygen electrodes.

Metal bellows are inferior to a series of partially-inflated plastic pillows in weight, volume, and volume change per unit collapsed volume. Metal bellows with an internal switch can be used to terminate charge, but weight and volume expenditures are comparable to that of one pressure transducer per cell.

Bellows action is recommended as a means of controlling electrolyte levels when desirable oxygen recombination rates and adequate discharge voltage can only be achieved in this manner. Application in space will require the elimination of all air spaces outside the cell pack except that in the bellows cavity. A minimum volume of 10 to 20% of the inside cell volume will be sacrificed to install the bellows device.

9. NEW TECHNOLOGY

A series of plastic pillows partially inflated and sealed individually from a flexible plastic film to serve as an expansion chamber in sealed cells for controlling electrolyte level is considered new technology. Such an assembly is a light weight substitute for a metal bellows, is much more adaptible to cell geometry, and provides a greater volume change per unit bellows volume. Material sources and sealing technique are given in Appendix A.

BIBLIOGRAPHY

(1) Contract NAS5-3813

(2) U.S. Patent 2,131,592, 27 September 1938, A.E. Lange et al.

(3) U.S. Patent 2,614,138, 14 October 1952, P.Q.C. Jacquier.

(4) U.S. Patent 3,208,884, 28 September 1965, D. C. Jensen.

(5) D.H. Collins, Batteries, Pergamon Press, 1963, p. 122.

(6) A.M. Chreitzberg, Seventh Biweekly Progress Report, JPL Contract 950495, September 1963.

APPENDIX A

PILLOW MATERIALS AND SOURCES OF SUPPLY

1. Broli Autoclavable Nylon Tubing (100' X 1-1/2" X 0.002") (made in Sweden) (Diversified Products Nylon Autoclavable Film No. 1041)

2. Stokes Molded Products Division, E.S.B., Trenton, N.J.

   Flat Tubing: Vinyl (1-5/16" wide X .017" thick)
   Flat Tubing: Polyallomer (1-1/16" wide X .014" thick)
   Flat Tubing: Polyethylene (1" wide X .016" thick)

3. Westlake Plastics Company, Lenni Mills, Pa. "Ethylux" sheeting in 10, 15 and 20 mil thickness Standard Pillow Floats

4. General Chemical Division of Allied Chemical Corporation, Morristown, N.J. "ACLAR" fluorohalacarbon film. R. F. sealed poucher of 9 mil Alcar, 22A.

5. Ivers-Lee Company, Newark, N.J. "3-DEE" packages combination 1L-D1-LEK 21 (Allied Chemical "ACLAR") (6 mils thick) (a fluro-halocarbon), 1L-D-6 (Minnesota Mining & Mfg. Co. "Scotchpak")

6. General Chemical Division, Allied Chemical Corporation, Charlotte N. C. Capran (polyamide) film thickness ≐ 3 mils.

7. Avisun Corporation, Philadelphia, Pa. Olefane A-25, polypropylene film, 4 mils thick, one side corona discharge treated for printability (Spec. 1000,EPO 387, No. 1-5632) also, untreated film.

8. Sealed Air Corporation, Hawthorne, N.J. "Aircap" small air filled capsules of thin Saran and polyethylene film.

9. Extron Corporation, Knoxville, Tenn. "Transtube" Flexible, clear, PVC tubing i.d. = 1/2, 3/4 and 1". Local distributor: Robert E. Mason & Associates, Inc., Charlotte, N. C.

10. Continental Can Co.

    Laminate of 1.5 mil polypropylene on 0.5 mil Mylar
    Laminate of 3 mil polyethylene on 0.75 mil Mylar
    Laminate of 1.5 mil medium density polyethylene on 0.5 mil Mylar.

11. The United States Stoneware Company, Akron, Ohio Tygon Flexible Plastic tubing, Formulation R-3603, 1" I.D., 1-1/4" O.D., 1/8" wall 1/2 I.D., 5/8 O.D., 1/16"

12. Commercial Plastics and Supply Corporation, Atlanta, Ga. "Astra/OS" extruded flexible tubing 3/4 I.D. X 35 mil wall (Decomposed by KOH) Polythylene sheet "Boronol" Type A, 20, 30, 60 and 90 mils thick.

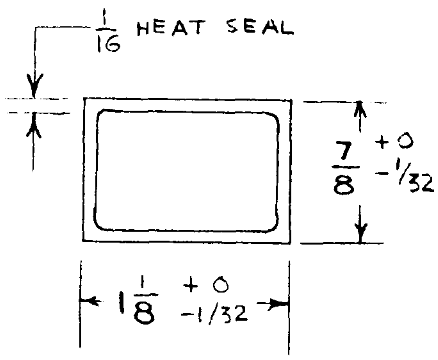
13. E. I. DuPont de Nemours and Company, Inc. "Surlyn A" thermoplastic. (Sheet or tube samples requested) (none received).

14. Shop Stock - Polyethylene sheet, 4 mils.

15. Adam Spence Corporation, Union, N. J. - KEL-F-81 tubing (used by J. A. Deknatel & Son, Inc., Queen Village, Long Island, N.Y. as a suture package).

PLASTIC PILLOW FOR MULTI-SECTION RECTANGULAR BELLOWS

MATERIAL = POLYPROPYLENE FILM - 4 MILS THICK PROD. BY AVISUN CO.



HEAT SEALING DIE FOR PLASTIC PILLOW

MATERIAL = BRASS

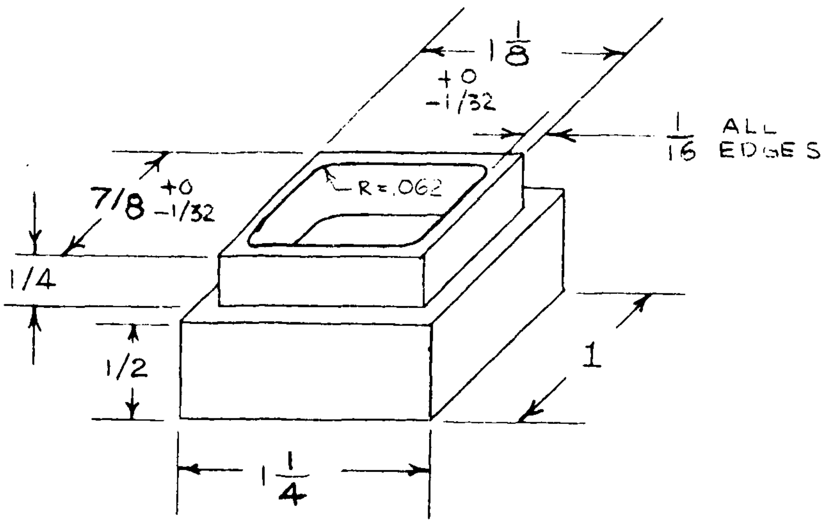


TABLE I

CHARACTERISTICS AND ESTIMATED PERFORMANCE
OF COMMERCIAL METAL BELLOWS

Supplier	Bellows Description	Bellows Characteristics		
		Part No.	ΔV/V*	Length**
Metal Bellows Corporation Sharon, Mass.	Welded diaphragm types in four basic contours: Flat plate, Nesting Ripple, Single Sweep and Torus. Material: stainless steels			
	Nesting Ripple Contour off-the-shelf Bellows type 347 stainless steel	A-20115	0.278	4.14
	P/N A-20115 Modified For Action from nested state		0.312	3.69
	Calc'd nesting ripple bellows of AM350 steel for action from completely nested state.		0.364	3.36
National Bellows Company Stratford, Conn.	Welded diaphragm flat plate type in stainless steel.	P/N 3401	0.237	5.15
Robertshaw-Fulton Controls Co.,Knoxville, Tenn.	Hydraulically formed single ply stainless steel bellows	Ref. #358	0.217	5.48
Servometer Corporation Clifton, N.J.	Miniature nickel bellows of electrodeposited type. O.D. Range: 0.063 to 1.25"	Max. PSI For Max. Stroke		
	Bellows calc.from listed data	34	0.247	4.97
	Bellows calc.from listed data	134	0.125	9.76
	Bellows calc.from listed data	77	0.174	7.06

(*) Maximum volume change per square chamber volume
(**) Length of 1" diameter bellows for a 20 cc volume change.

TABLE I

CHARACTERISTICS AND ESTIMATED PERFORMANCE
OF COMMERCIAL METAL BELLOWS
(continued)

Supplier	Bellows Description	Bellows Characteristics		
		Type	$\Delta V/V$	Length (Inches)
Miniflex Corporation Lawndale, Calif.	Miniature stainless steel bellows O.D. Range 0.226 to 1.270	SS-750-65-97	0.144	8.29
Keller Products Company Hanover, N. J.	Welded diaphragm nickel and stainless steel bellows in four contours including "nesting types".	BEB-160-7500	0.110	11.1
		BEB-160-6103	0.012	98.6
U.S. Flexible Tubing Co. Bartlett, Illinois	Stainless steel bellows	1/2x3/4	0.160	11.6
B. F. Goodrich Company Aerospace and Defense Products Div. Akron, Ohio	Omega design seamless bellows. Hydraulic and mechanical processes. O.D. range 1/4 to 1 1/2" Stainless steel bellows-switch Ass'n B.F.G. Dwg.C3K1060	3K-1060	0.037	32.8

TABLE II

ELECTROLYTE LEVEL VARIATION IN 4 A.H. Ni-Cd CELL CONTAINING POLYETHYLENE PILLOWS WITH EXTERNALLY IMPOSED PRESSURE CHANGES

Imposed Pressure PSIA	Electrolyte Levels* Free Electrolyte Volume	
	45cc	55cc
	Plate Immersion %	Plate Immersion %
4.8	87.9	Flooded
7.3	59.8	95.1
9.8	37.8	72.0
12.7	23.2	59.8
14.7	15.9	51.2
29.7	5mm Below Bottoms	28.1
44.7	6mm Below Bottoms	22.0
59.7	7mm Below Bottoms	18.3
64.7	8mm Below Bottoms	17.1

(*) Separator: Single layer of 9XX nylon cloth.
Electrolyte: 20% KOH

TABLE III

ELECTROLYTE LEVEL VARIATION DURING CHARGE AND OPEN-CIRCUIT
OF 4 A.H. CELL WITH DOUBLE NYLON CLOTH SEPARATORS AND PILLOWS

Cell Function	Time Elapsed (Hrs.)	Cell Pressure PSIA	Electrolyte Level	
			Distance Below Plate Tops mm	% Immersion
Open Circuit	Start	.9	21	74.4
C/10 Charge	9.5	7	62	24.4
	10.5	9	68	17.1
	14.0	18	82	0
Open-Circuit	2	12	74	9.8
	4	8	64	22.0
	19.6	2	28	65.8
	29	.9	24	70.8
Continued C/10 Overcharge	15.5	47	Below Bottoms	0
Open-Circuit	0.3	44	Below Bottoms	0
	0.7	41	Below Bottoms	0
	4.8	15	--	--
	10.5	6	--	--
	23	3	39	52.5
	120	.9	21	74.4
C/10 Charge after discharge at C/2 Rate	11.3	0	79	3.7
	12.1	3.5	82	At Bottoms
	13.0	8.0	84	Bellow Bottoms

TABLE IV

PHYSICAL CHARACTERISTICS OF NETTING TYPE SEPARATORS

Separator Material	Thickness δ Mils	Mesh Size L Mils	Mesh Size W Mils	Mesh Opening Area A Per In^2 Material Mils^2 X 10^4	Ratio $\frac{A}{\delta}$ X10^4	Electrolyte Absorption Mg/in^2/Mil	Electrolyte Retention* cc/in^2 x 10^{-2}	Plate Immersion* (%)
Teflon screen AGB 9-200-74	8	2.9	2.9	24.3	3.04	4	9.4	98
Nylon mono-filament Cloth AGB 120 mesh	7	5.4	5.4	41.0	5.85	8	11.5	100
Same 96 Mesh	8	6.3	6.3	36.6	4.57	12	10.2	98
Teflon screen AGB 9-60-250	10	9.8	9.8	43.1	4.31	6	--	43
Teflon screen AGB 9-45-350	16	13.7	13.7	38.6	2.41	8	--	28
Teflon screen AGB 9-40-420	23	16.5	16.5	37.3	1.62	1.2	9.5	30
Teflon screen AGB 9-18-100	30	39.4	39.4	50.3	1.68	0.12	9.5	18
Nalle "Rice Bag" Netting	16	105 L	75 8	52.4	3.28	1.9	7.6long axis 8.2 short axis	18
DuPont Vexar 15 ADS 129 netting	23	90 L	55 S	25.7	1.12	1.2	8.2long axis 8.4short axis	18

δ = Thickness of the diffusion layer
L = Long axis of diamond
S = Short axis of diamond

* After 2 minutes simple drain

TABLE V

CHARGE AND DISCHARGE CHARACTERISTICS OF 4 A.H. Ni-Cd CELLS WITH NETTING AND WOVEN CLOTH SEPARATOR MATERIALS

Test Parameter	Separator System					
Separator Material	DuPont Vexar Net (23 Mils)		Nalle Net (16 Mils)		A.G.B. Nylon Cloth (8 Mils)	
Electrolyte Concentration,%	25	20	25	20	25	20
A. Open Cell Discharge Tests: (1) (2)						
1. Flooded Cell Capacity, A.H. 100% Plate Immersion	5.58	5.20	4.66	5.36	4.40	4.80
2. Cell Capacity, A.H. 50% Plate Immersion	3.60	3.90	3.50	3.64	4.58	4.62
Capacity, % Flooded Capacity	65	75	75	68	104	96
3. Cell Capacity, A.H. 10% Plate Immersion	1.10	1.58	1.32	1.30	4.08	4.02
Capacity, % Flooded Capacity	20	30	28	24	93	88
B. Sealed Cell Charge Tests:						
1. Charge and Overcharge						
Input at C/10 rate, A.H.	1.2	1.2	4.90	4.90	7.3	7.3
Input at C/20 rate, A.H.	0.8	4.2	1.80	1.99	5.1	5.1
Second Input at C/10 rate, A.H.	--	--	--	--	19.2	19.2
Total Input, A.H.	2.0	5.4	6.7	6.89	31.6	31.6
2. Test End Voltage, Volts	1.545	1.51	1.54	1.51	1.49	1.45
3. Maximum Cell Pressure, Abs. Atm.	0.53	2.9	0.57	4.4	1.5	4.2
4. Plate Immersion, % at Test End (3)	26	16	40	27	10	15

Notes: (1) Each charge 16 hours at C/10 rate = 6.4 AH input.
(2) Each discharge at C/2 rate to 1.00 volt per cell
(3) Initially plates were 100% immersed

TABLE VI

AUTOMATIC FLEXING TEST ON PILLOW TYPE BELLOWS SUBSTITUTES
IMMERSED IN 25% KOH ELECTROLYTE
AT ROOM TEMPERATURE

Flex Cycle: 11 Seconds Evacuation to 28" Hg
1 Second Exhaust

Pillow Material	Dimensions Inside Seal	Sealing Method	Displacement Under Water: Volume Empty (cc)	Displacement Under Water: Volume With Air At.Patm. (cc)	Displacement Under Water: With Air Under Vac 28" Hg (cc)	Volume Change ($V_{vac.} - V_{atm}$) = ΔV (cc)	Pillow Efficiency $\frac{\Delta V}{V\ Vac}$	Flexing Cycles To Failure
Polyethylene Sheet, 4 mil, Double Layer	1 3/4 X 1 7/8	Flame	1.5	2.75	14.0	11.25	0.805	297 (1)
Polyethylene Sheet, 4 mil, Double Layer	1 3/4 X 1 7/8	Hot Wheel	2.0	3.0	14.0	11.0	0.785	79 (1)
Polyethylene Sheet, 4 mil, Single Layer	1 3/4 X 1 7/8	Hot Wheel	1.0	2.0	17.0	15.0	0.882	20 (2)
Swedish Nylon Autoclave Tubing 2 Mils, Single Layer	1 15/16 X 1 1/2	Flame	0.25	1.5	16.0	14.5	0.905	700+(3)
Capran (Polyamide) Film, 2 mils Single Layer	1 3/4 X 1 7/8	Flame	0.5	1.75	15.0	13.25	0.884	7000 (1)
Polypropylene Film, 3.5 Mils, Single Layer	2 X 1 7/8	Hot Wheel	1.4	2.0	12.5	10.5	0.84	6000+(4)
Capran, 2 mils, Single Layer Inside Polyethylene, 4 mils, Single Layer	1 3/4 X 1 3/4 1 15/16 X 1 7/8	Flame Hot Wheel	0.75	2.25	18.0	15.75	0.875	670 (1)
Stokes, Polyallomer, Flat Tube 14 Mils	1 1/16 X 1 3/4	Hot Press	2.0	2.0	4.0	2.0	0.50	+25,000(4)
Stokes, Polyethylene, Flat Tube 16 Mils	1 X 1 3/4	Hot Press	1.5	2.5	4.0	1.5	0.374	+6,000(1)
Stokes,Vinyl,Flat Tube, 17 mils	1 5/16 X 1 3/4	Hot Press	2.0	2.5	6.0	3.5	0.584	49,000(4)
Polyethylene Sheet, 20 mils Single Layer	1 1/2 X 1 7/8	Hot Press	2.5	3.25	6.0	2.75	0.458	715 (2)
Polyethylene Sheet, 20 mils Single Layer	1 3/4 X 1 7/8	Hot Press	3.5	5.0	6.0	1.0	0.17	320

TABLE VII

DESIGN FACTORS FOR SIX AMPERE-HOUR Ni-Cd TEST CELLS
FOR
BELLOWS AND SEPARATOR SYSTEM EVALUATION

Separator System	Oxygen Electrode	No Bellows	Bellows or Pillows			
			20 cc Nickel	10 cc Nickel	40 Units Pillows	50 Units Pillows
P	Yes	9 (control)				
D	Yes		1	2	3	4
A	Yes		5	6	7	8
B	Yes			10	11	
	No			12	13	
C	No		14			
	Yes		15			

Notes:
(1) All cells have 6 positive sintered Ni plates 1.75" x 3.25"x 0.050".
(2) All cells have 7 negative Cd plates 1.75" x 3.25" x 0.050".
(3) All cells have 1.40 charged negative/charged positive capacity ratio.
(4) All cells have 20% KOH electrolyte at 50% immersion (1 atm) except control cell S/N 9 which was force drained.
(5) All cells were evacuated until plates were immersed 100% before sealing except control cell S/N 9 which was sealed force drained at 1 atmosphere.
(6) Separator systems:

P	1L	Pormax PVC, 10 mil
D	1L	4 mil nylon cloth
	1L	10 mil Teflon screen (AGB 9-60-250)
A	1L	10 mil Teflon screen (AGB 9-60-250)
B	2L	4 mil nylon cloth (AGB 8 M) (8 mils total thickness)
C	B plus 11 mil strands or polypropylene wrapped around negative plates vertically.	

TABLE VIII

EVALUATION TEST SCHEDULE
FOR 6 AMPERE-HOUR BELLOWS CONTROLLED
Cd/KOH/NiOOH CELLS

Step	Test Description	Test Cell Description and Assignment
1	BELLOWS CALIBRATION 1.1 Compression Stroke Test 1.2 Expansion Stroke Test 1.3 Composit Stroke Test	All metallic bellows and pillows as indicated
2	MANUAL BASELINE TESTS	Initial Test Group:
2.1	Open Cell Discharge Capacity Rates = C/5, C/2, C/1 Temperatures = 0°C and 25°C Electrolyte Levels = 100%, 50%, 10% Control Group = Force Drained	Cells 1, 2, 3, Nylon cloth sep's. Cells 5, 6, 7, Teflon screen sep's. Sealed Cell Control Group: Cell No. 4 Nylon cloth sep's. Cell No. 8 Teflon screen sep's. Cell No. 9 Pormax sep's.
2.2	SEALED CELL OVERCHARGE CAPABILITY Rates=C/20, C/10, C/5, C/2 Temperatures = 0°C and 25°C Electrolyte Levels = 50%, 10% drained	Initial test group (6 cells) Control group (3 cells)
3	PROOF CYCLE TESTS (Partially Automatic and Fully Monitored)	
3.1	Room Temperature Tests Levels = Select from baseline results Rates = Select from baseline results Cycle @ 24-hr. orbit for 10 cycles Cycle @ 8-hr. orbit for 40 cycles Adjustments = Rates and levels as needed during cycling to optimize	Electrolyte Level Control 20 cc Bellow / 10 cc Bellow / Pillows Cell No. 1 / Cell No. 2 / Cell No. 3 Cell No. 5 / Cell No. 6 / Cell No. 7 Sealed cell control group
3.2	Extreme Temperature Tests Level = Optimum from 3.1 results Rates = Select from 3.1 results Cycle @ 24-hr. orbit for 10 cycles Cycle @ 8-hr. orbit for 40 cycles Adjustments = Rates and levels as needed during cycling to optimize	Temp. Groups / Level Control: 20 cc Bellow / 10 cc Bellow / Pillow 0°C / Cells 1&14 / Cells 2&10 / Cells 3&11 40°C / Cells 5&15 / Cells 6&12 / Cells 7&13 Separators: Optimized for cells 10 thru 15 Control Group: 0°C, 5 cycles at 24 hours and 20 cycles on 8-hr. orbit, repeat at 40°C.
4	FINAL CYCLE TESTS (Fully automatic and partially monitored)	
	Continuous cycling on shortest possible orbit to establish repeatability	Temperature Groups 0°C: Cell Nos. 10, 11, 15 25°C: Cell Nos. 1, 2, 3 40°C: Cell Nos. 5, 6, 7, 12, 13, 15 Control Group At all 3 temperatures

TABLE IX

FINAL DATA AT EACH STAGE DURING OVERCHARGE CAPABILITY
TEST OF NINE 6 A.H. SEALED Ni-Cd CELLS - SIX CELLS WITH BELLOWS
AND THREE WITH LIMITED ELECTROLYTE TO ACT AS "CONTROL" CELLS

Test Step		Test Cell Groups								
		Control Group (No Bellows)			Nylon-Teflon Sep. Group			Teflon Sep. Group		
Cell Number *		4 NY-Tef	8 Tef.	9 Pormax	1 20cc B	2 10cc B	3 31-P	5 20cc B	6 10cc B	7 31-P
Charge at C20	Hrs.	26	41	41	41	41	41	41	41	41
	V	1.59	1.56	1.40	1.40	1.40	1.40	1.40	1.41	1.46
	PSIA	21	17	35	18 ½	28	24	20	21	20
	Level %	--	--	--	62	60	64	60	62	57
Overcharge @ C/10	Hrs.	--	1/2	24	24	24	24	24	24	1/2
	V	--	1.72	1.40	1.40	1.45	1.41	1.46	1.48	1.55
	Press.	--	25	54	23	43	35	23	25	22
	Level	--	--	--	42	45	47	47	52	52
Overcharge @ C/5	Hrs.	--	--	4	4	0.1	4	0.1	0.1	--
	V	--	--	1.42	1.44	1.55	1.43	1.59	1.64	--
	Press.	--	--	83	30	--	46	--	--	--
	Level	--	--	--	23	--	39	--	--	--
Open Circuit Stand	Hrs.	45	29-1/2	2	2	6	2	6	6	29-1/2
	V	1.32	1.33	1.33	1.34	1.34	1.34	1.34	1.34	1.33
	Press.	17	21	44	12.7	9.8	21	11.8	8.8	10.8
	Level	--	--	--	87	--	73	--	--	--
Dischg. @ 2.0 Amps	Hrs.	1.13	2.28	2.62	2.67	2.48	2.62	2.61	2.65	2.85
	V	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Press.	17	21	25	7.3	6.9	13.2	9.3	5.4	9.9
	Level	--	--	--	95	86	96	90	84	98

(*) NY-Tef = Sep. of 1 layer nylon cloth plus 1 layer teflon screen.
Tef. = Sep. of 1 layer teflon screen only.
Pormax = Sep. of microporous PVC sheet.
20 cc B= Metal bellows of 20 cc capacity.
10 cc B= Metal bellows of 10 cc capacity.
31-P = Polypropylene bellows of 31 pillow units.

TABLE X

CONCENTRATION AND LEVEL CHANGES IN ELECTROLYTE
DURING CHARGE AND DISCHARGE*

Reaction in Positive Plate Compartment During Charge	Reaction in Negative Plate Compartment During Charge	Net Change in Electrolyte Level	
		Positive Compartment	Negative Compartment
System: Cd/KOH/NiOOH On Nickelic Oxide Plates: $2\ Ni(OH)_2 + 2\ \overline{OH} \longrightarrow$ $2\ NiOOH + 2H_2O + 2e$ $[\overline{OH}]$ falls during charge. $[HOH]$ rises during charge.	On Cadmium Plates: $CdO + H_2O + 2e \longrightarrow$ $Cd + 2\overline{OH}$ $[\overline{OH}]$ rises during charge. $[HOH]$ falls during charge.	No change. No membrane to create osmotic effect.	No change. No membrane to create osmotic effect.
System: Cd/KOH/AgO On AgO Plates: $Ag + 2\overline{OH} \longrightarrow$ $AgO + H_2O + 2e$ $[\overline{OH}]$ falls during charge. $[HOH]$ rises during charge.	On Cadmium Plates: $CdO + H_2O + 2e \longrightarrow$ $Cd + 2\overline{OH}$ $[\overline{OH}]$ rises during charge. $[HOH]$ falls during charge.	Membrane present. Water transferred out. <u>Electrolyte level falls.</u>	Membrane present. Water transferred in. <u>Electrolyte level rises.</u>
System: Zn/KOH/AgO On AgO Plates: $Ag + 2\overline{OH} \longrightarrow$ $AgO + H_2O + 2e$ $[\overline{OH}]$ falls during charge. $[HOH]$ rises during charge.	On Zinc Plates: $ZnO + H_2O + 2e \longrightarrow$ $Zn + 2\overline{OH}$ $[\overline{OH}]$ rises during charge. $[H_2O]$ falls during charge.	Membrane present. Water transferred out. <u>Electrolyte level falls.</u>	Membrane present. Water transferred in. <u>Electrolyte level rises.</u>

(*) All processes shown are reversed during discharge.
(**) Cd $(OH)_2$ is a preferred reactant. Reaction written to show consumption of H_2O.

TABLE XI

SEALED Ag-Cd TEST CELL DESIGN FEATURES

Design Features	Unit	Number	Characteristic	Volume %
1. Plate Pack				
Positives	ea	4	1.95" x 3.09" x .020	
Negatives	ea	5		
2. Theoretical Capacity				
Ag	AH	per cell	16.8	
CdO	AH	per cell	34.8	
3. Oxygen Electrode	ea	2	2.06" x 3.87" x .010"	
4. Cell Outside Dimensions	in			
Length			1.19	
Width			2.40	
Height			5.80	
5. Outside Volume	in^3		16.4	
6. Cell Pack Dimensions	in		0.97 x 2.15 x 3.70	
7. Cell Pack Volume	in^3		7.7	63.6
8. Bellows Assembly				
Number of Pillows	ea	30		
Pillow Size, Deflated	in		0.88 x 1.25 x .008	
9. Bellows Cavity				
Dimensions	in		0.97 x 2.15 x 1.18	
Volume	in^3		2.5	20.7
10. Air Space (Above Plates)				
Dimensions	in		0.97 x 2.15 x 0.20	
Volume	in^3		0.4	3.3
11. Seal & Supports Volume	in^3		1.5	12.4
12. Inside Cell Volume	in^3		12.1	100.00
13. Cell Weight (less gauge)	lb		0.93	

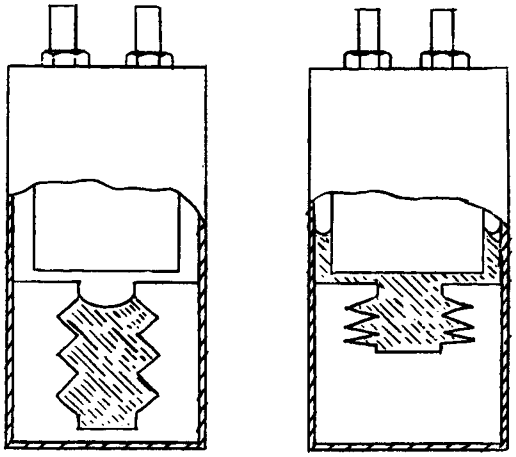
TABLE XII

DESIGN FEATURES OF 100 A.H. Ag-Cd CELL WITH BELLOWS

Characteristic	Design Value				
1. Cell Dimensions, Inches	Outside, max.				Inside, min.
Length	1.767				1.402
Width	4.718				4.360
Height	9.390				8.672
Volume, In^3	78.0				53.1
2. Cell Pack					
Plate Dimensions, Inches	Length		Width		Height
Six (6) positives	.033	x	4.20	x	6.50
Seven (7) negatives	.110	x	4.20	x	6.50
Two (2) oxygen electrodes	.010	x	4.20	x	7.12
3. Active Material Weight, gms					
Positive silver	6 x 66.1 = 397				
Negative CdO	6 x 131 = 786				
4. Capacity, A.H.					
Theoretical					
(+) Plates	197				
(-) Plates	328				
Expected Output, 10 hr. rate					
(+) Plates	110				
(-) Plates	196				
5. Bellows Cavity Dimensions, Inches					
Length	1.402				
Width	4.360				
Height	1.188				
Volume, In^3 (%)	7.27 (9.3)				
6. Electrolyte Volume, cc 40% KOH	446				
7. Weight Analysis, gms					
Dry Cell Pack	1610				
Jar + Cover + Epoxy Seal	390				
Electrolyte	630				
Bellows Cage + Assembly	60				
Total Cell Weight, gms (lbs)	2690 (5.9)				
8. Energy Density 10 Hr. Rate					
WH/lb	20.5				
WH/in^3	1.6				

FIGURE 1

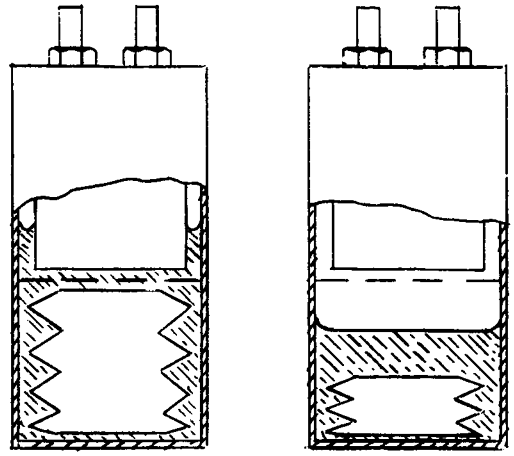
TYPICAL BELLOWS INSTALLATIONS IN SEALED CELLS



Bellows Extended In Overcharge

Bellows Collapsed After Discharge

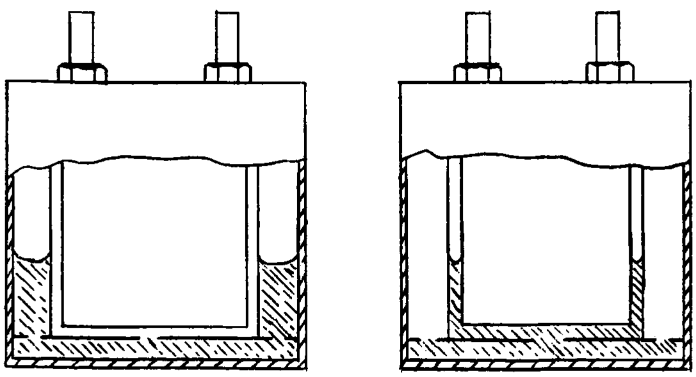
A
Internal Actuation



Bellows Extended After Discharge

Bellows Collapsed In Overcharge

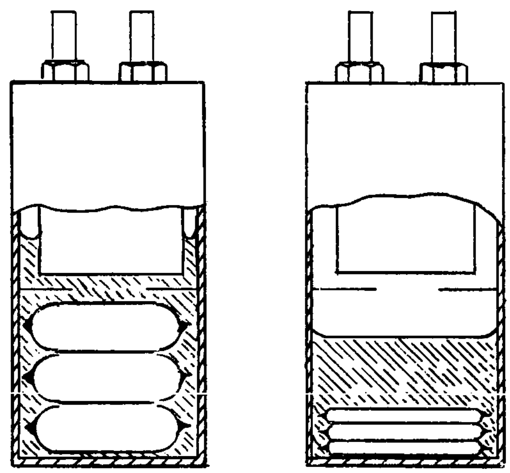
B
External Actuation



Air Space Compressed In Overcharge

Air Expanded After Discharge

C
Bellows Replaced By Air Chamber



Pillows Expanded After Discharge

Pillows Compressed During Overcharge

D
Bellows Replaced By Partially Inflated Pillows

FIGURE 2

CELL PRESSURE AND BELLOWS CONTROLLED ELECTROLYTE LEVEL
DURING 24-HOUR ORBIT CYCLING OF 4 AH Ni-Cd SEALED CELLS

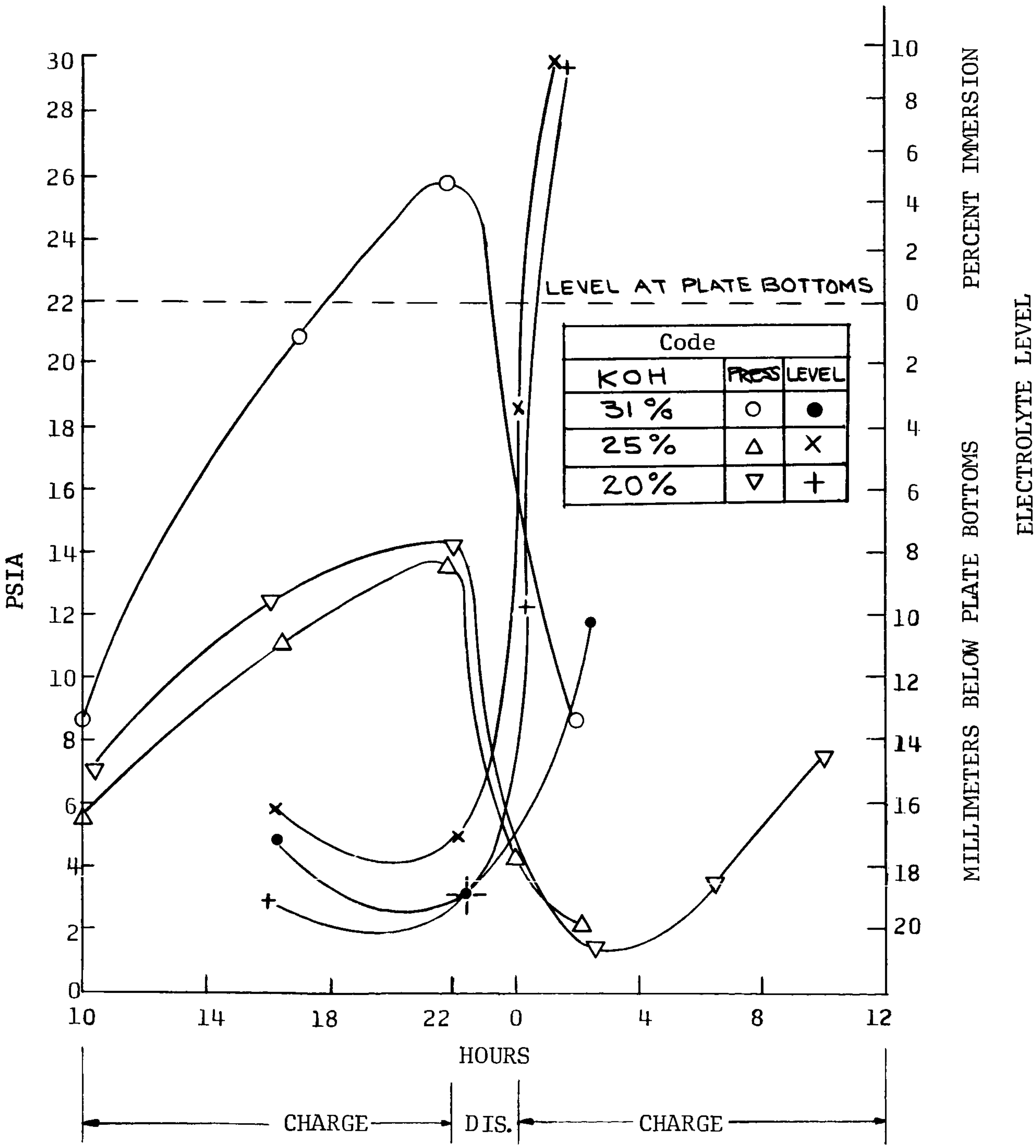


FIGURE 3

CELL PRESSURE AND BELLOWS CONTROLLED ELECTROLYTE LEVEL
DURING 2-HOUR ORBIT CYCLING OF 4 AH Ni-Cd SEALED CELLS: CYCLES 13-28

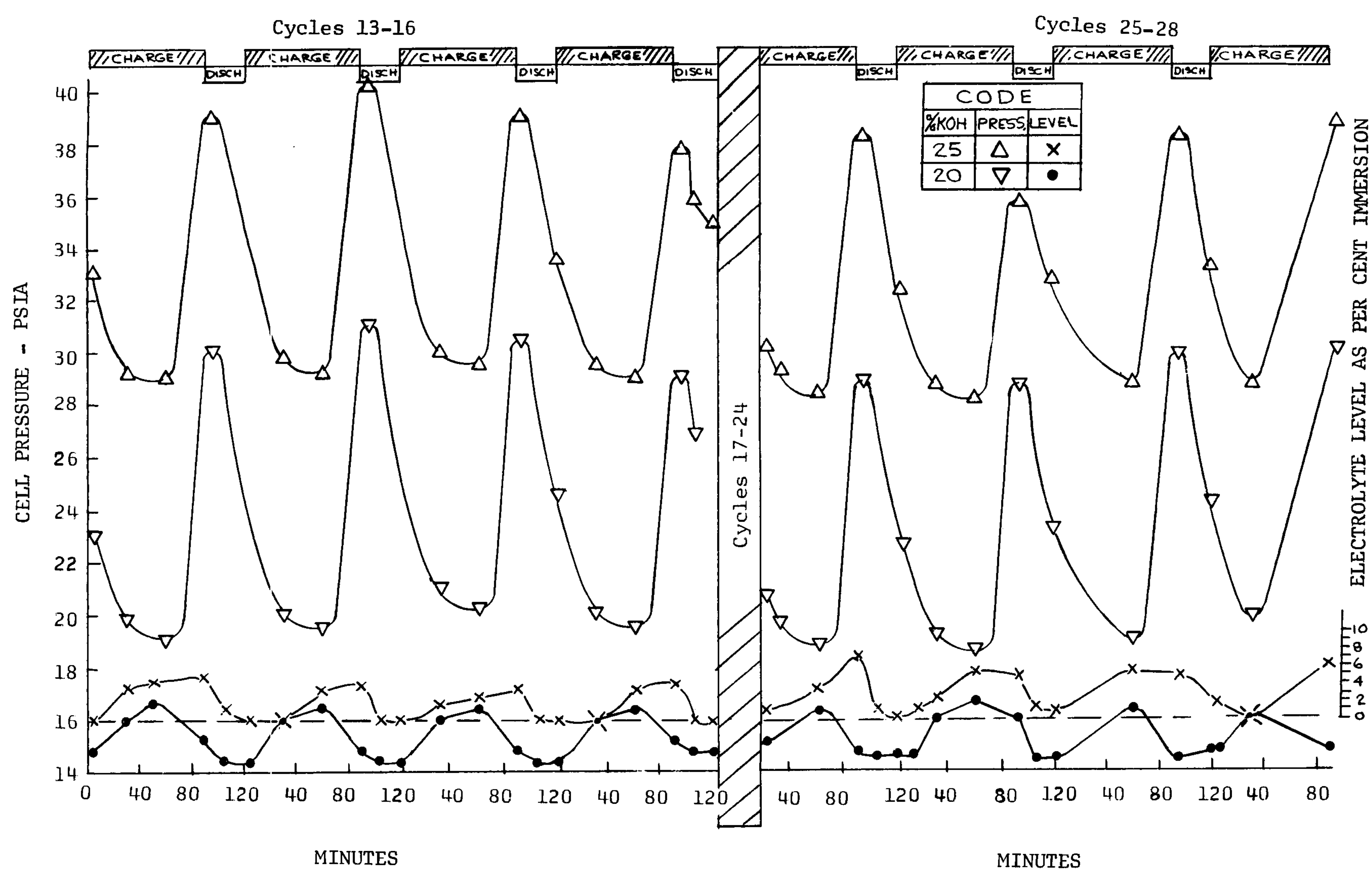


FIGURE 4

EFFECT OF OPEN WEAVE SEPARATOR MATERIALS ON CHARGE AND OVERCHARGE VOLTAGE PRESSURE AND BELLOWS CONTROLLED ELECTROLYTE LEVEL IN 4 AH Ni-Cd CELLS WITH 25% KOH

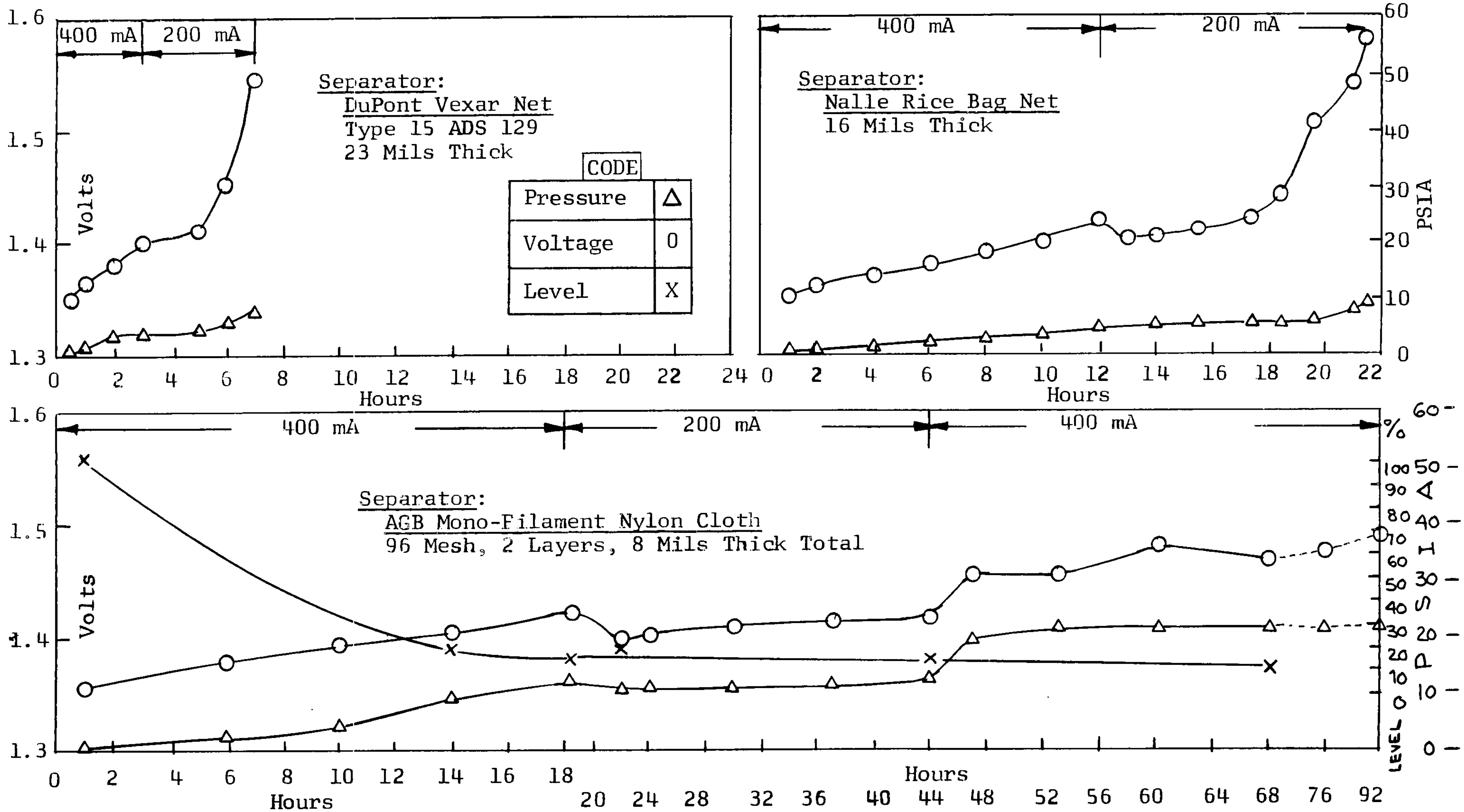


FIGURE 5

EFFECT OF OPEN WEAVE SEPARATOR MATERIALS ON CHARGE AND OVERCHARGE VOLTAGE
PRESSURE AND BELLOWS CONTROLLED ELECTROLYTE LEVEL IN 4 AH Ni-Cd CELLS WITH 20% KOH

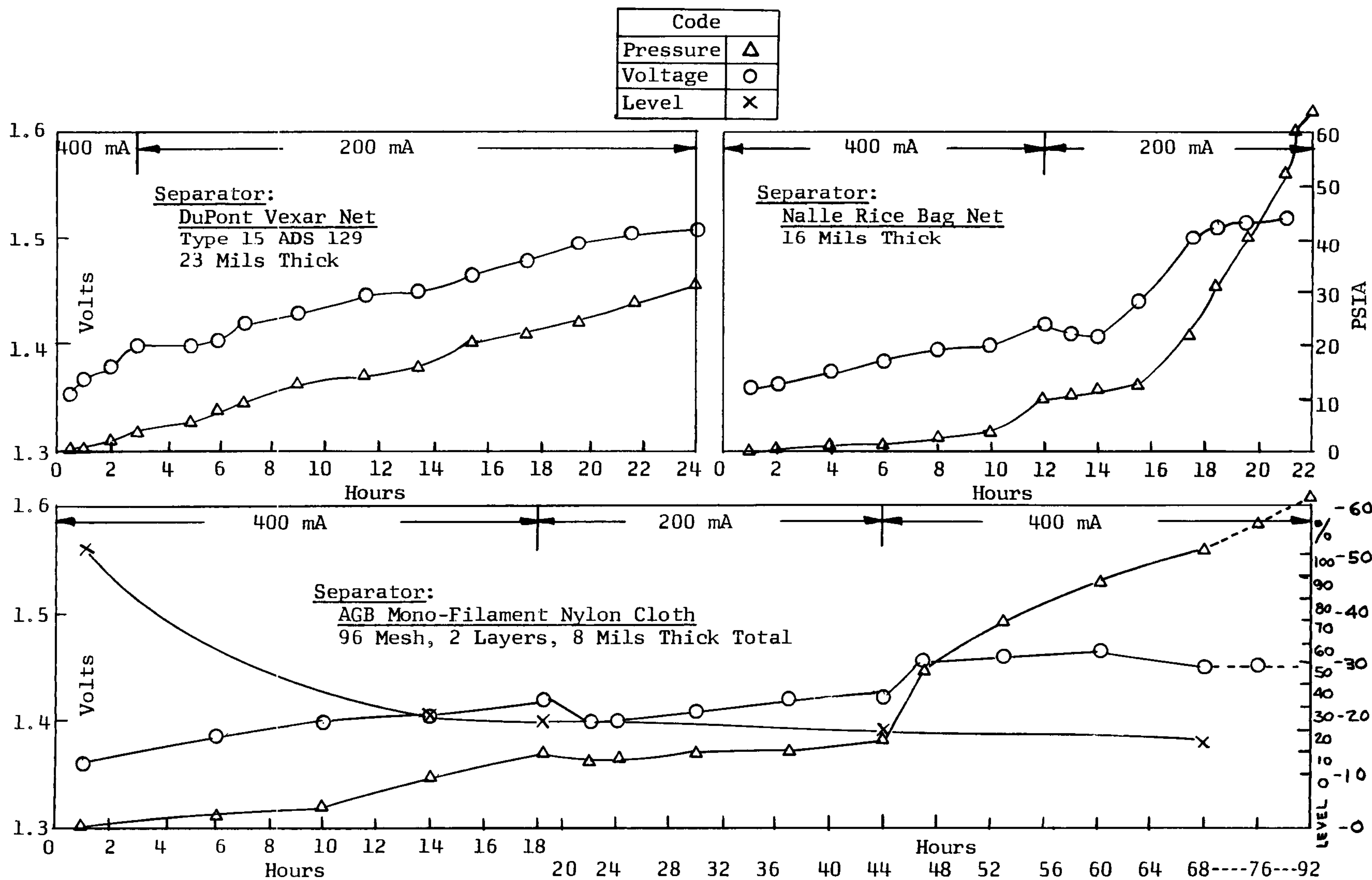
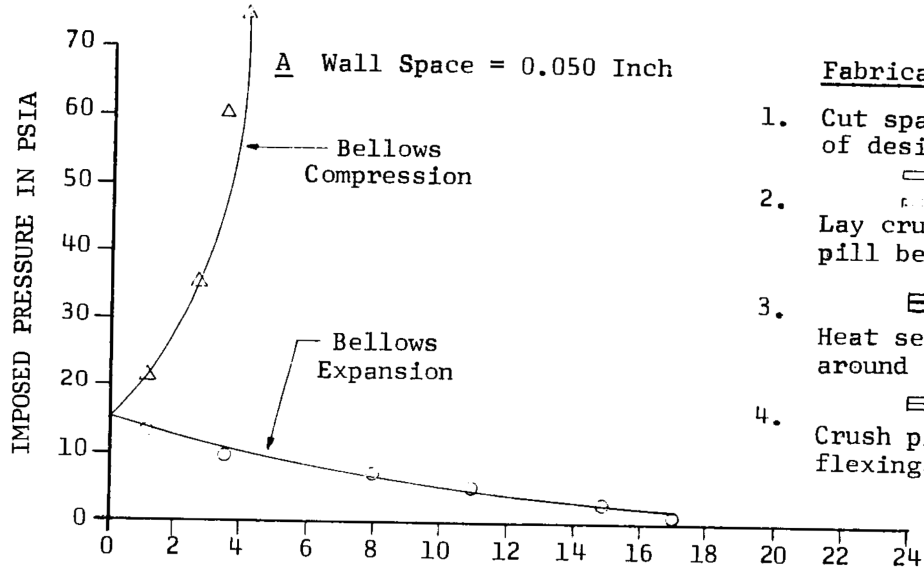


FIGURE 6

EFFECT OF PILLOW WALL SPACING (TRAPPED AIR VOLUME)
ON ACTION OF 22 UNIT POLYPROPYLENE BELLOWS



Fabrication of Pillow Unit

1. Cut spacer pill from stock of desired thickness.

2. Lay crushable foam plastic pill between film.

3. Heat seal 1/16 inch rim all around to trap air and pill.

4. Crush pill to make room for flexing.

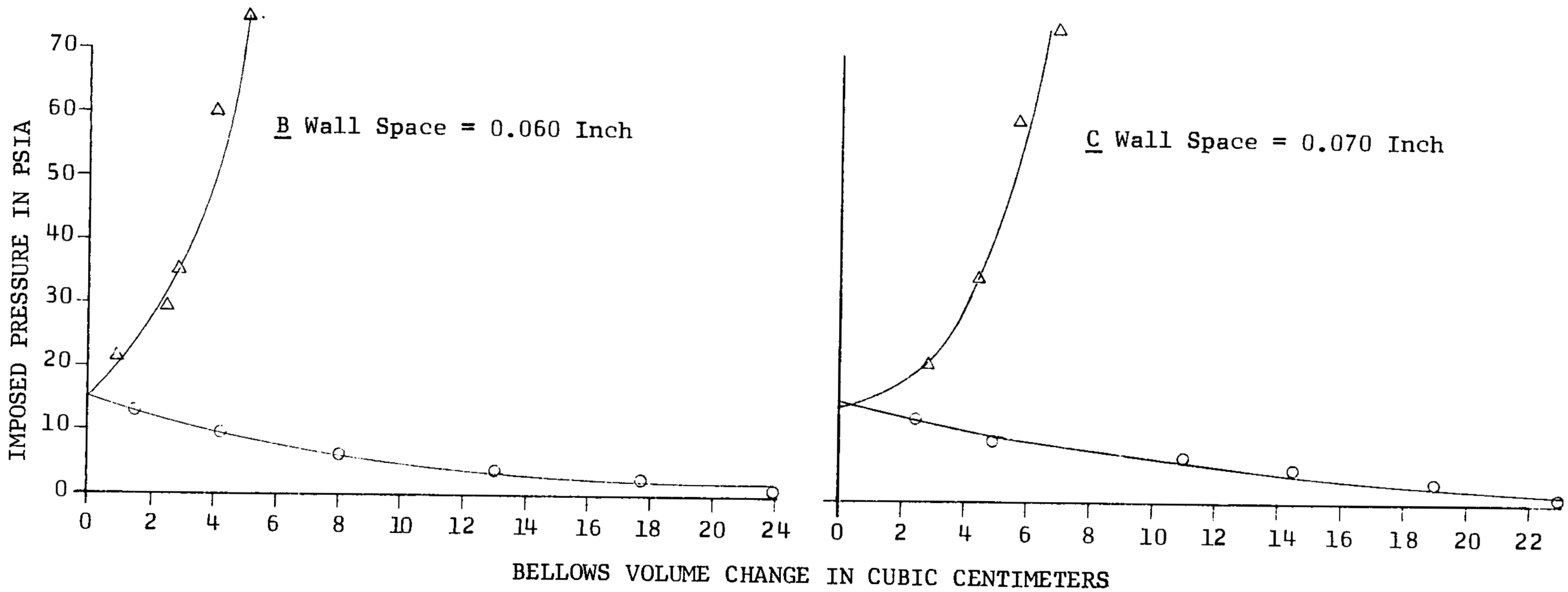


FIGURE 7

ACTION OF POLYPROPYLENE FILM BELLOWS WITH
DIFFERENT NUMBERS OF PILLOW UNITS IN A GIVEN CHAMBER

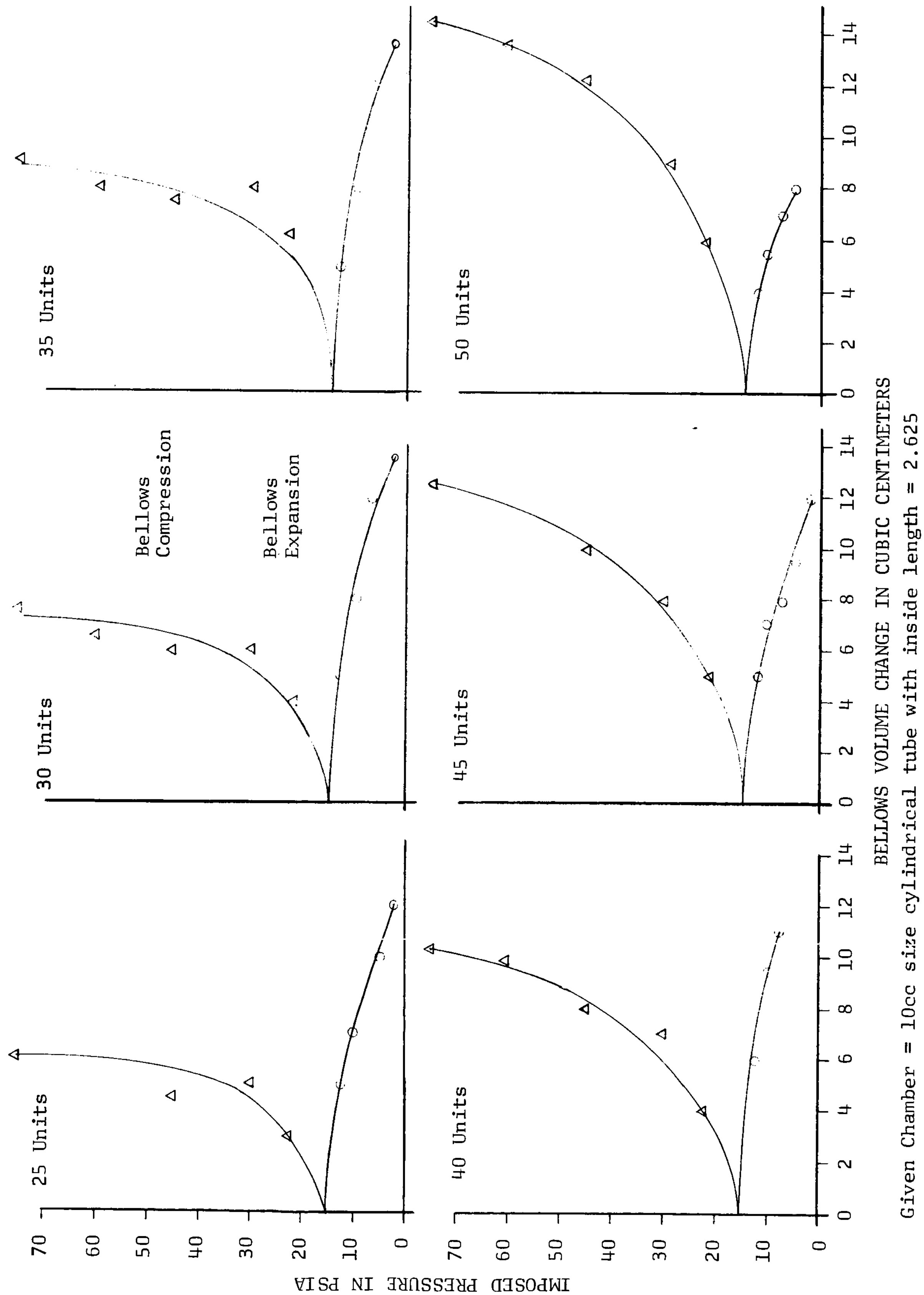


FIGURE 8

COMPARISON OF POLYPROPYLENE PILLOW
ASSEMBLY WITH NICKEL BELLOWS ACTION

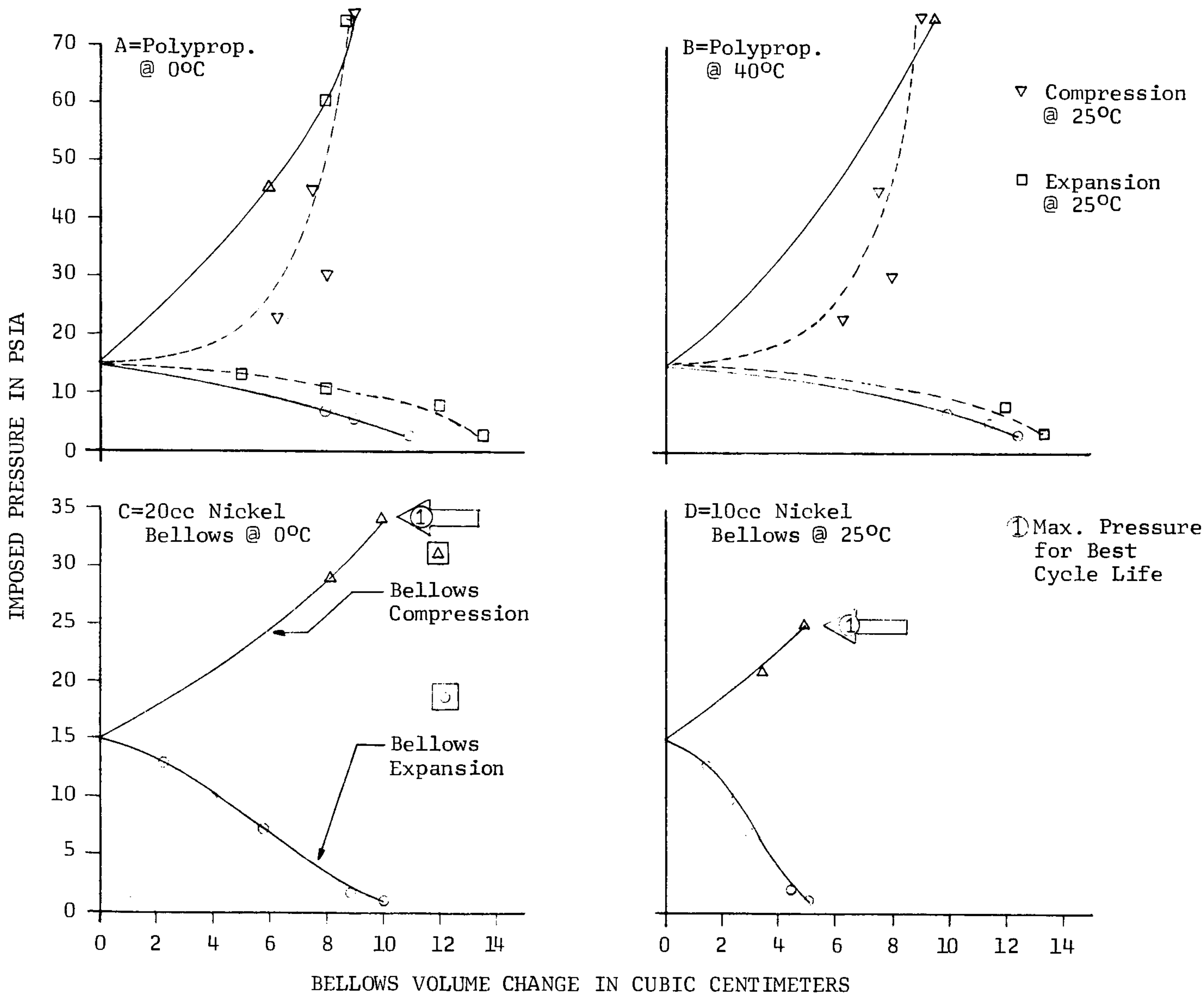


FIGURE 9

DISCHARGE VOLTAGE CHARACTERISTICS AT C/5 RATE (1.2 Amps) FOR VENTED, 6AH, SINTERED PLATE Ni-Cd CELLS AT ELECTROLYTE LEVELS OF 10%, 50%, AND 100% IMMERSION AND THREE DIFFERENT SEPARATORS

CODE Immersion Level	Symbol
100%	○
50%	△
10%	▽

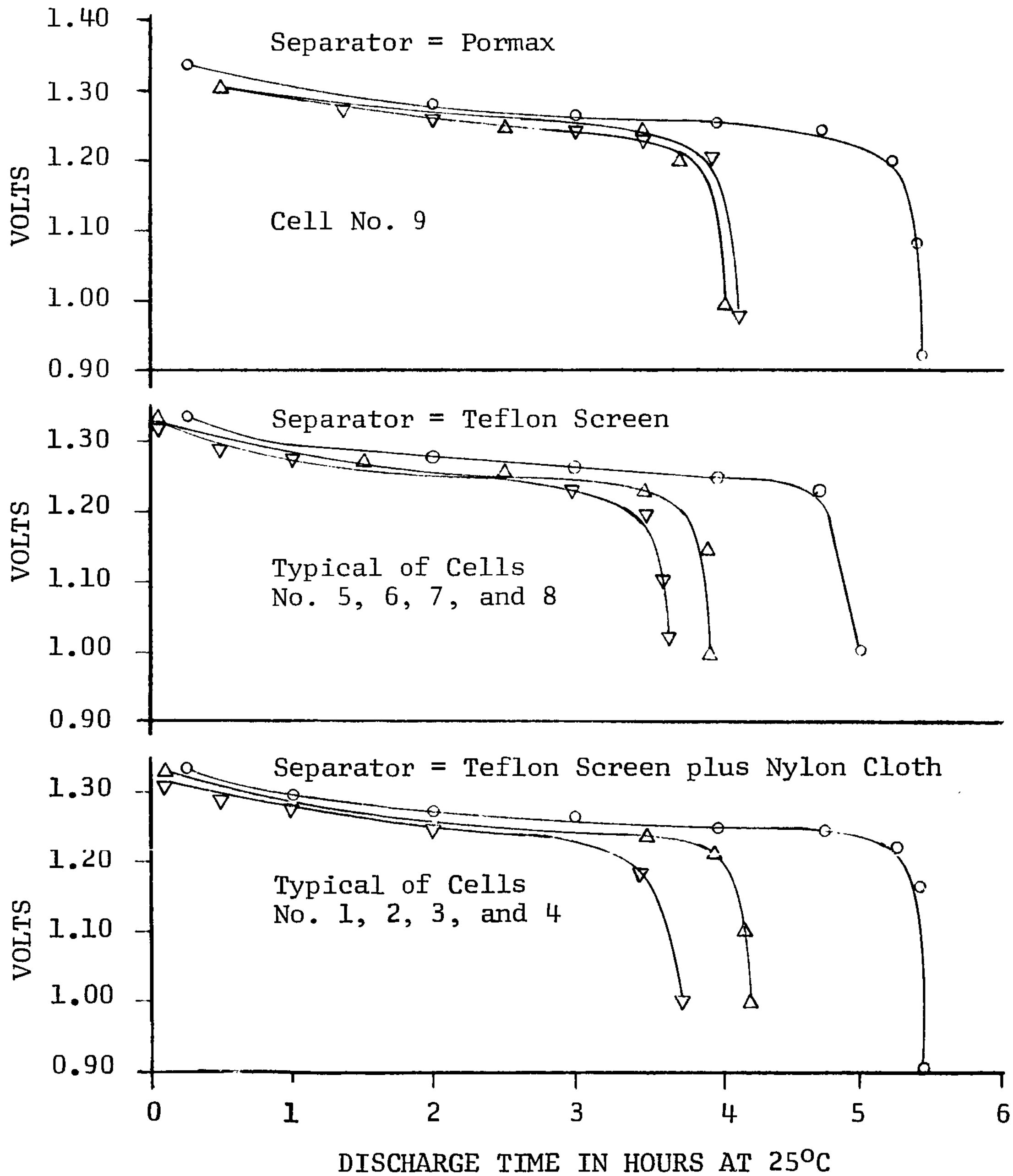


FIGURE 10

DISCHARGE VOLTAGE CHARACTERISTICS AT C/2 RATE (3.0 Amps)
FOR VENTED, 6AH, SINTERED PLATE Ni-Cd CELLS AT
ELECTROLYTE LEVELS OF 10%, 50%, AND 100%
IMMERSION AND THREE DIFFERENT SEPARATORS

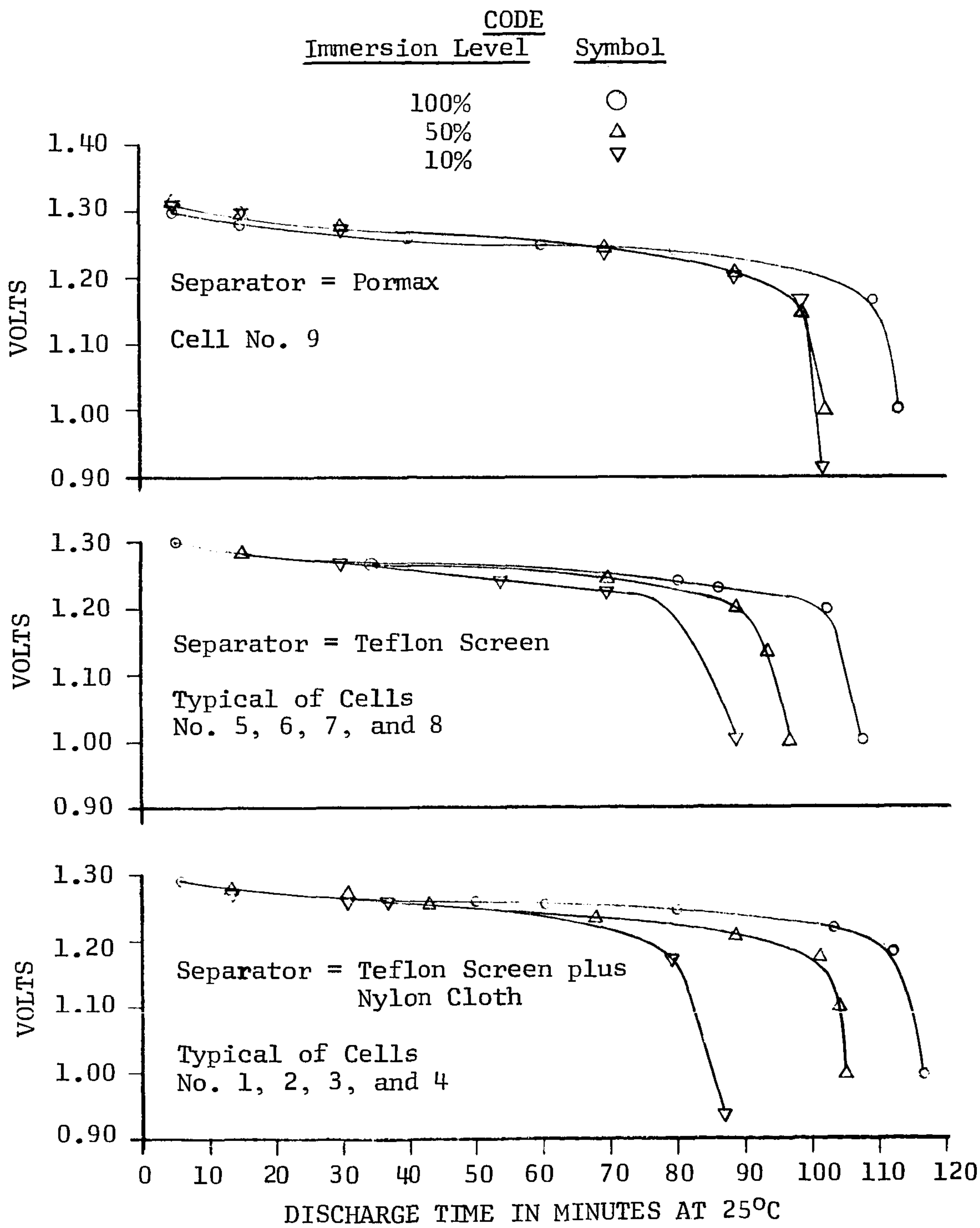


FIGURE 11

DISCHARGE VOLTAGE CHARACTERISTICS AT C/1 RATE (6.0 Amps) FOR VENTED, 6AH, SINTERED PLATE Ni-Cd CELLS AT ELECTROLYTE LEVELS OF 10%, 50%, AND 100% IMMERSION ON THREE DIFFERENT SEPARATORS

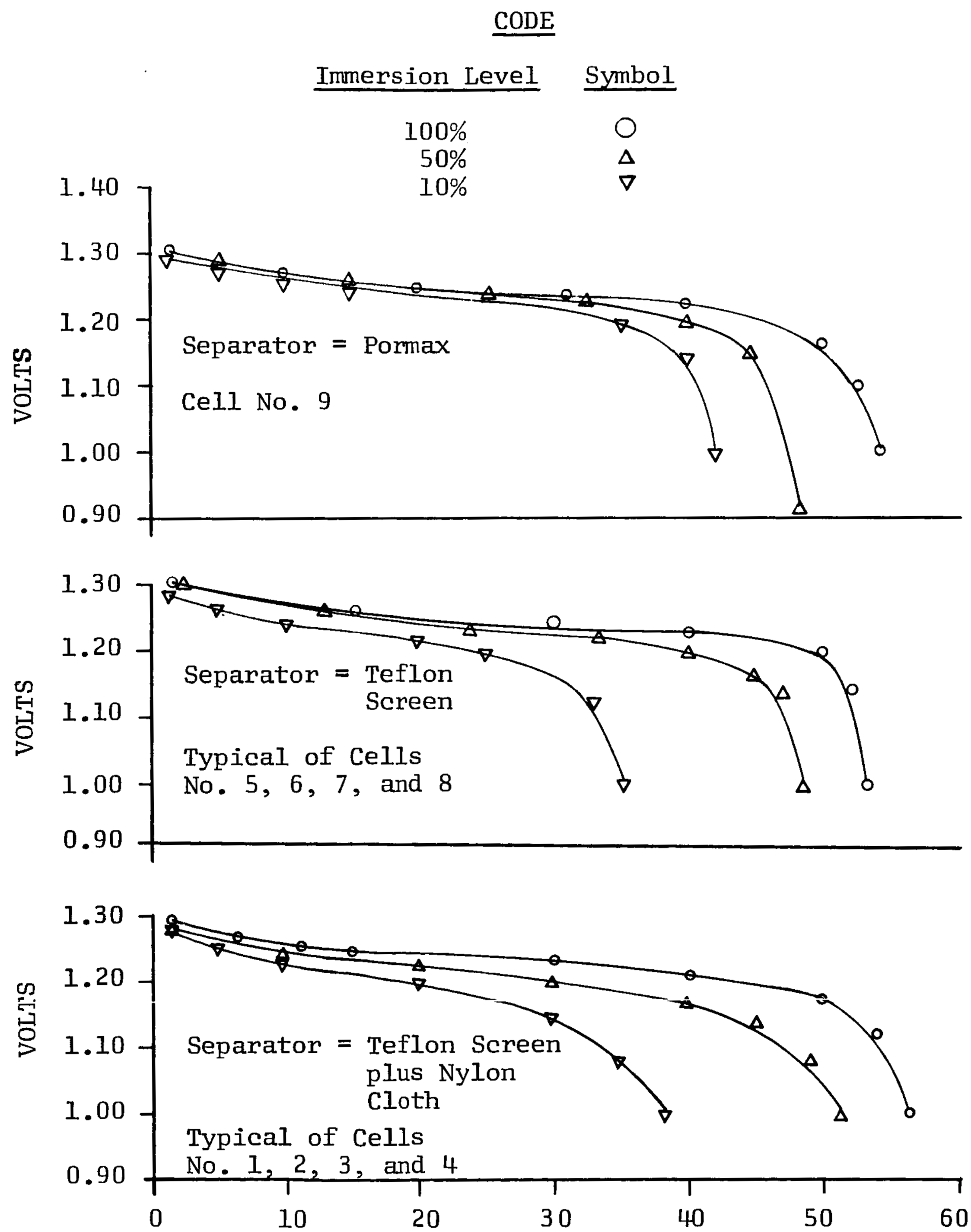


FIGURE 12

EFFECT OF OXYGEN ELECTRODE DURING OPEN CIRCUIT RECOVERY AFTER ROOM TEMPERATURE OVERCHARGE OF BELLOWS EQUIPPED 6AH Ni-Cd CELLS

Cell No.	Oxygen Electrode	Separator	Bellows	Fill Level	Seal	Cell Press.	% Level
6-10	Yes	NY	10cc Metal	50%	Evac. to Flood	△	X
6-12	No	NY	10cc Metal	50%	Evac. to Flood	▽	o
6-11	Yes	NY	40 Pillows	50%	Evac. to Flood	△	X
6-13	No	NY	40 Pillows	50%	Evac. to Flood	▽	o
6-14	No	NY+FILS	20cc Metal	50%	Evac. to Flood	▽	o
6-15	Yes	NY+FILS	20cc Metal	50%	Evac. to Flood	△	X

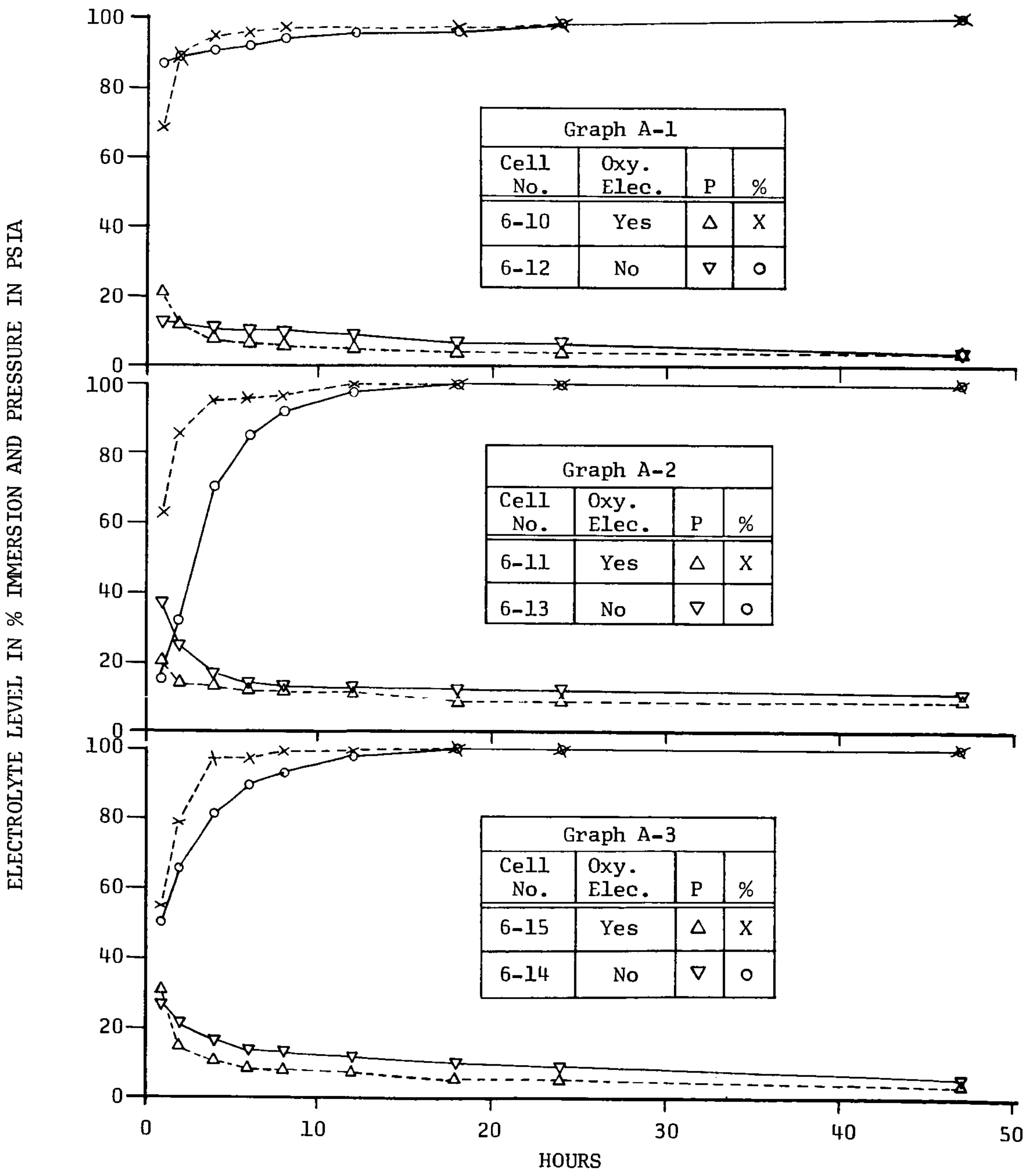


FIGURE 13

EFFECT OF OXYGEN ELECTRODE ON BELLOWS ACTION AT 0^oC AND 40^oC
DURING 24-HOUR CYCLING OF 6 AH NICKEL CADMIUM CELLS

Orbit Regime: Chg. 22 Hrs. at C/5 - Disch. 2 Hrs. To 0.5 C Output

Cell No.	Separator	Bellows	Fill Level	Oxygen Electrode	Seal	V	PSIA	% Level
6-11	NY	40 Pillows	50%	Yes	Evac. to Flood	○ (small)	---△---	---×---
6-13	NY	40 Pillows	50%	No	Evac. to Flood	○ (large)	—▽—	—●—
6-14	NY Fils	20cc Metal	50%	No	Evac. to Flood	○ (large)	—▽—	—●—
6-15	NY Fils	20cc Metal	50%	Yes	Evac. to Flood	○ (small)	---△---	---×---

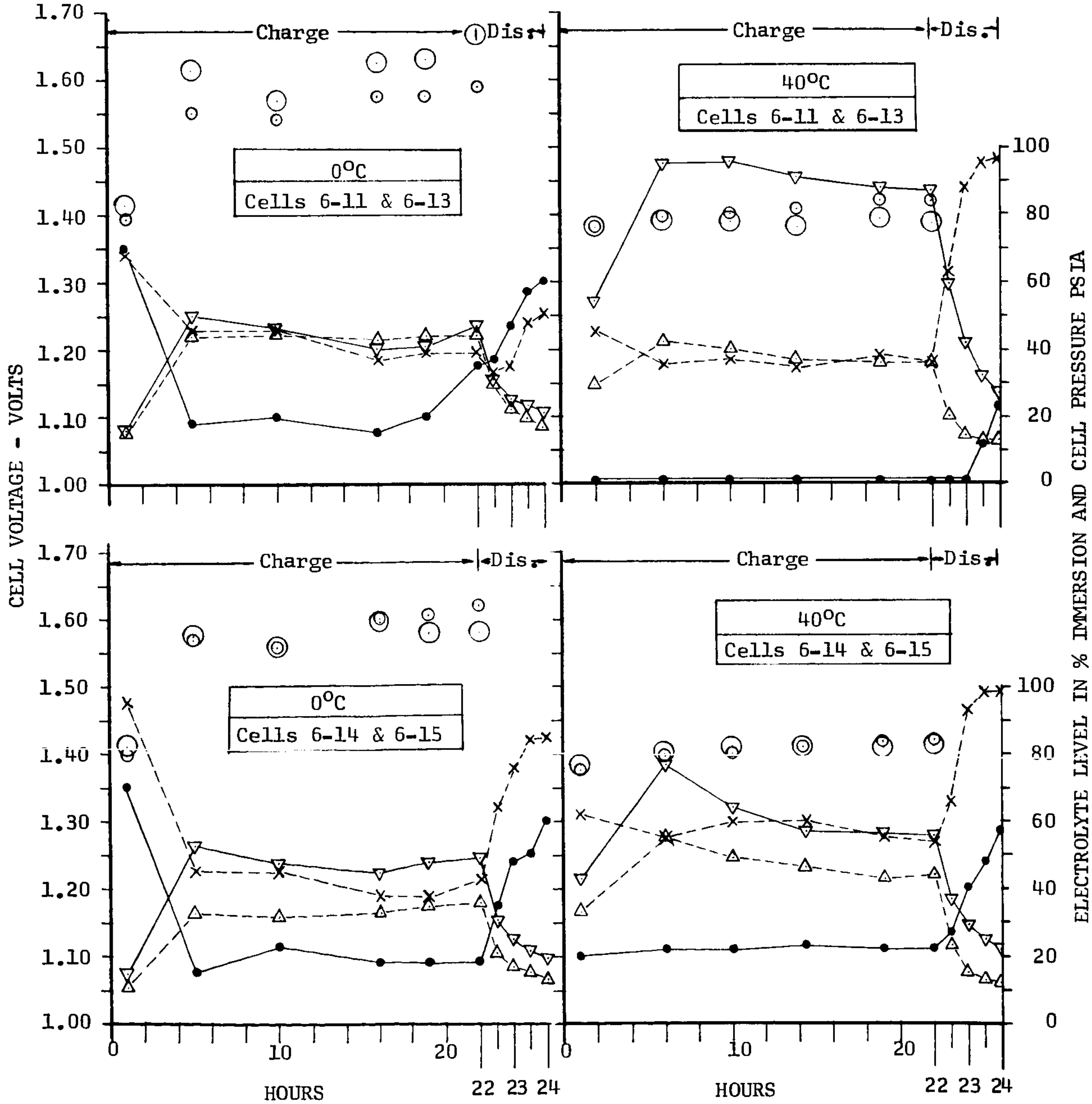


FIGURE 14

EFFECT OF ELECTROLYTE FILL LEVEL ON BELLOWS ACTION
IN 6 AH SEALED NICKEL CADMIUM CELLS DURING
24-HOUR ORBIT ROOM TEMPERATURE CYCLING

Orbit Regime: Charge = 22 Hrs. @ 1 Amp. (3.6C Input @ C/6 Rate)
Disch. = 2 Hrs. @ 1.65 Amps. (0.55C Output)

Fill Level	Cell No.	Separator	Bellows	Oxygen Electrode	Seal
50%	6-4	NY-TEF	50 Pillows	Yes	Evac. to Flood
67%	6-4	NY-TEF	50 Pillows	Yes	Evac. to Flood
50%	6-8	TEF	50 Pillows	Yes	Evac. to Flood
33%	6-8	TEF	50 Pillows	Yes	Evac. to Flood

Plotting Code

Fill Level	V	PSIA	Percent Level
50%	○ (small)	---△---	---×---
67 & 33%	○ (large)	---▽—	—●—

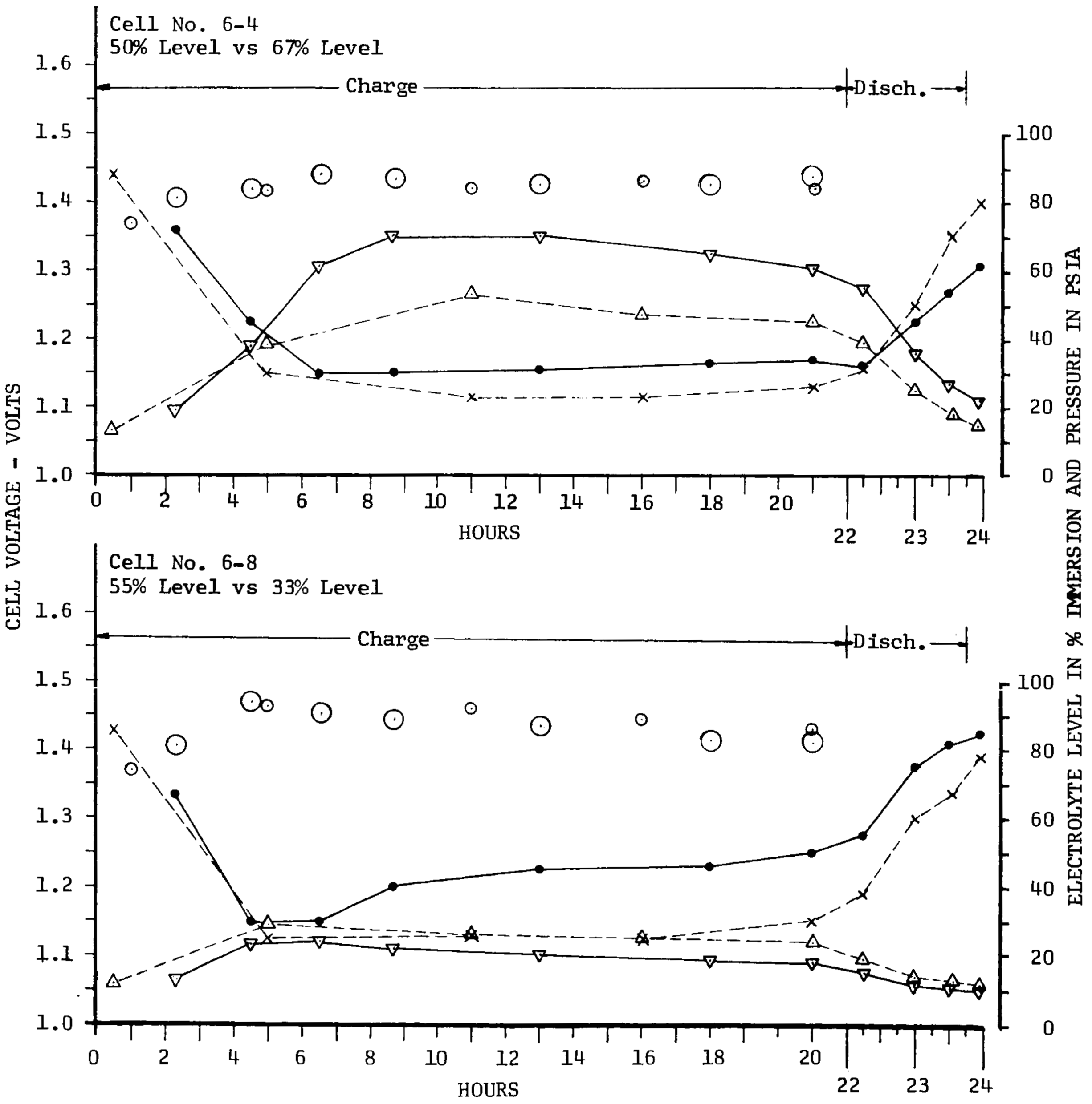


FIGURE 15

BELLOWS ACTION IN SEALED 6 AH NICKEL CADMIUM CELLS
WITH NY-TEF AND TEF SEPARATORS DURING 24-HOUR ORBIT AT 25°C

Orbit Regime:
Charge = 22 Hrs. @ 1 Amp. (3.6C Input @ C/6 Rate)
Disch. + 2 Hrs. @ 1.65 Amps. (0.55C Output)

Sep. & Cell No. NY-TEF	TEF	Bellows	Fill Level	Oxygen Electrode	Seal
6-1	6-5	20 CC Metal	50%	Yes	Evac. to Flood
6-2	6-6	10 CC Metal	50%	Yes	Evac. to Flood
6-4	6-8	50 Pillows	50%	Yes	Evac. to Flood
6-3	6-7	40 Pillows	50%	Yes	Evac. to Flood
6-9	Control	None	Limited	Yes	Evac.

Plotting Code

Separator	V	PSIA	Percent Level
NY-TEF Nylon Cloth + Teflon Screen Combination	○	--△--	—×—
TEF Teflon Screen Only	◯	--▽--	—●—
Pormax	◊	--□--	None

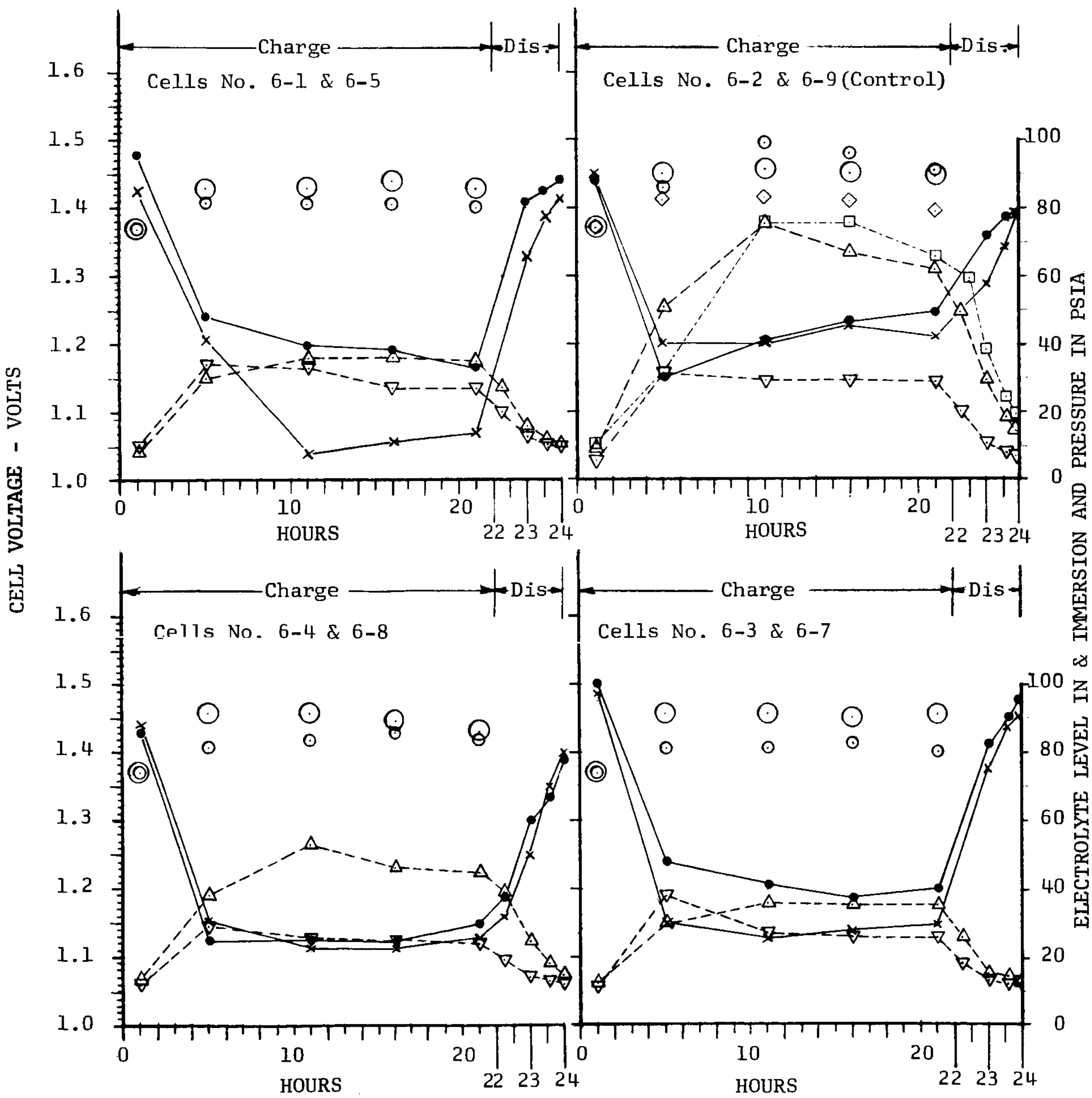


FIGURE 16

DISCHARGE CHARACTERISTICS OF SEALED
6 AH Ni-Cd CELLS WITH BELLOWS

Orbit Regime: Charge 22 Hrs. @ 1 Amp.
Discharge 2 Hrs. @ 1.65 Amps.

Temperature: 25°C

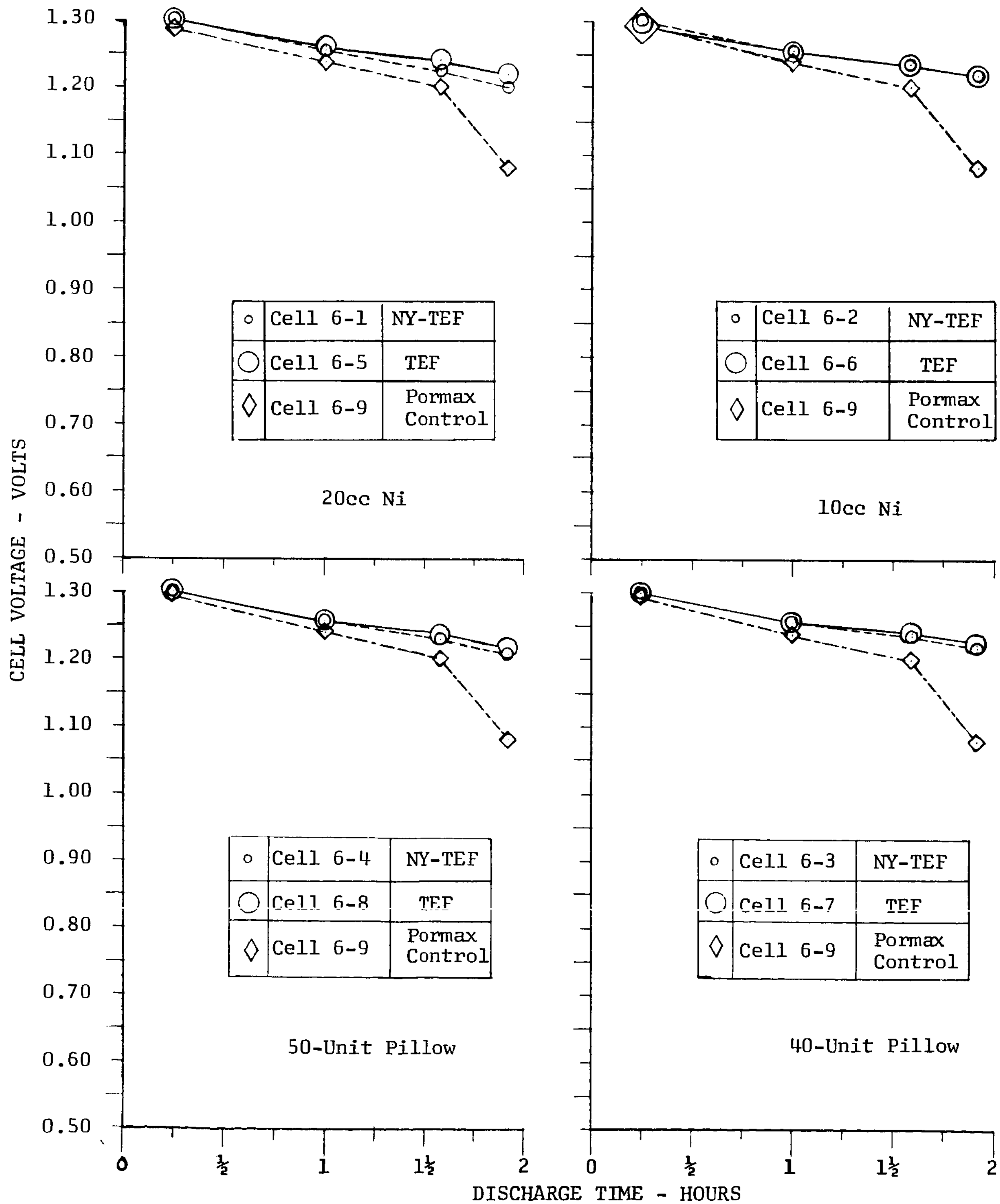


FIGURE 17

BELLOWS ACTION AT 0°C COMPARING NICKEL METAL BELLOWS
AND POLYPROPYLENE PILLOW TYPE IN 6 AH NICKEL CADMIUM CELLS

Orbit Regime:
Charge = 22 Hrs. @ C/20 - Also 22 Hrs. @ C/10
Disch. = 2 Hrs. @ 1.5 Amps. (0.50C Output)

Parameters and Plotting Code									
Bellows	Cell No.	Separator	Fill Level	Oxygen Electrode	Seal	Charge Rate	V	PSIA	Percent Level
20 CC Metal	6-5	Teflon Screen	33%	Yes	Evac. to Flood	C/20 (0.3 Amp.)	○	---Δ---	---X---
45 Pillows	6-7	Teflon Screen	33%	Yes	Evac. to Flood		◯	--▽--	—●—
20 CC Metal	6-5	Teflon Screen	33%	Yes	Evac. to Flood	C/10 (0.6 Amp.)	○	---Δ---	---X---
45 Pillows	6-7	Teflon Screen	33%	Yes	Evac. to Flood		◯	—▽—	—●—

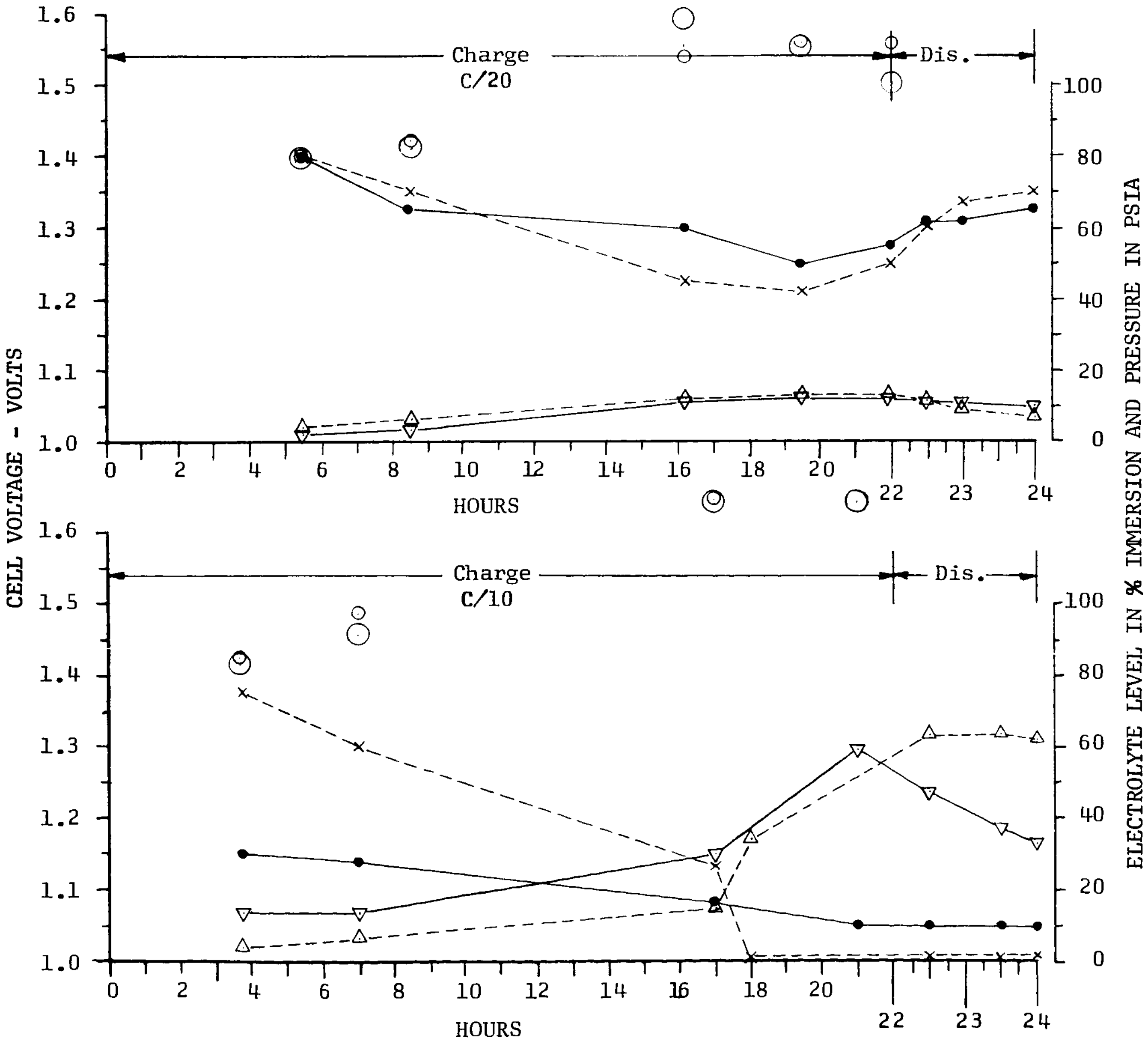


FIGURE 18

BELLOWS ACTION DURING 8 HOUR ORBIT CYCLING
OF 6 AH NICKEL CADMIUM CELLS AT ROOM TEMPERATURE

Orbit Regime: Charge = 7 Hrs. @ C/5
Disch. = 1 Hr. to 0.7CC

Cell No.	Separator	Bellows	Fill Level	Oxygen Electrode	Seal	V	PSIA	Percent Level
6-1	NY-TEF	20 CC Metal	67%	Yes	Evac. to Flood	○	△	×
6-2	NY-TEF	10 CC Metal 10 Pillows	50%	Yes	Evac. to Flood	◯	▽	•
6-3	NY-TEF	45 Pillows	67%	Yes	Evac. to Flood	○	△	×
6-4	NY-TEF	50 Pillows	67%	Yes	Evac. to Flood	◯	▽	•
6-9 Control	Pormax	None	Limited	Yes	Evac. to Flood	◊	□	None

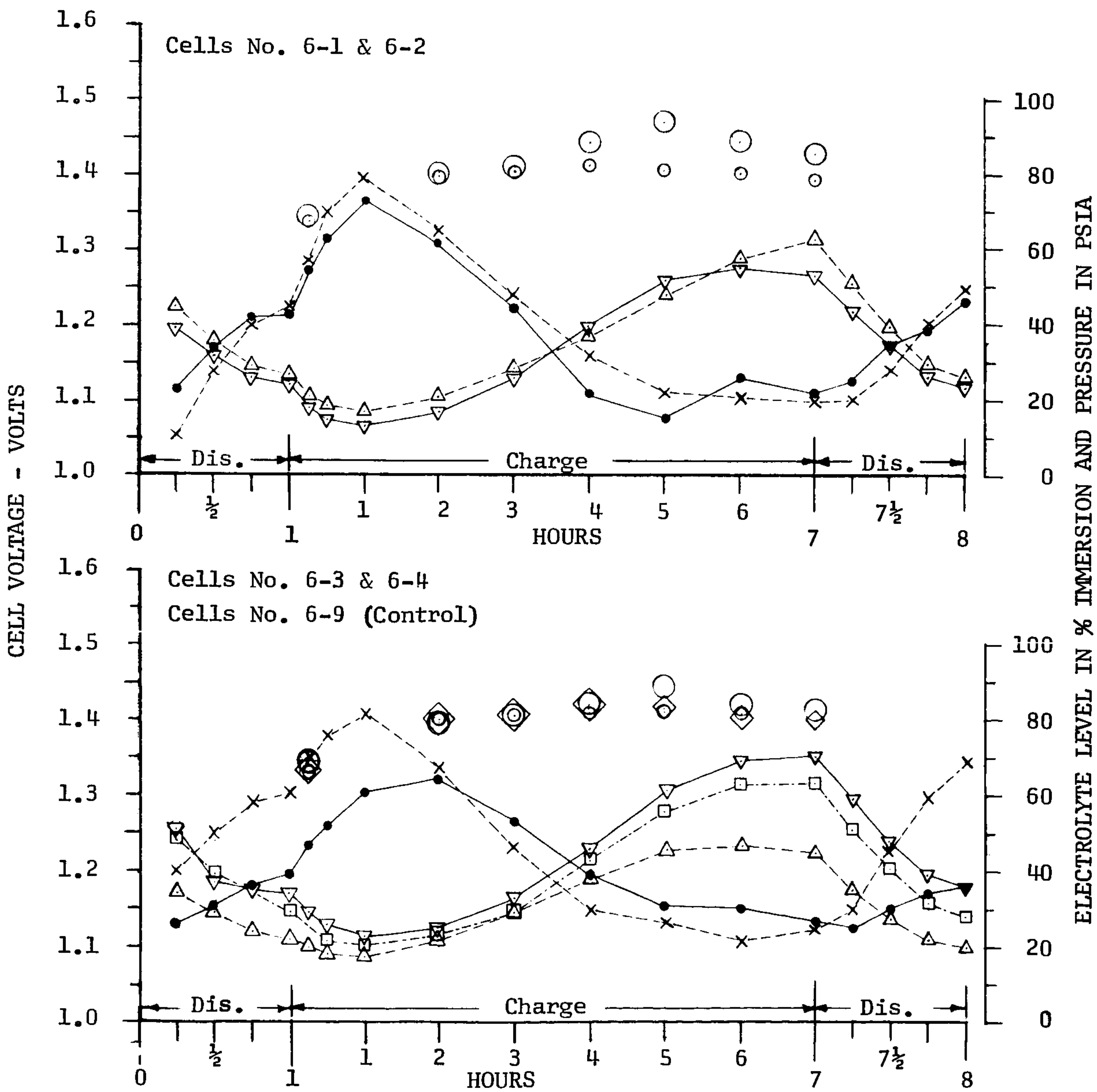


FIGURE 19

DISCHARGE CHARACTERISTICS OF SEALED 6 AH NICKEL CADMIUM CELLS WITH BELLOWS DURING 8 HR. ORBIT CYCLING

Orbit Regime: Charge 7 hours @ C/5
Discharge 1 hour to 0.7C

Temperature: 25°C

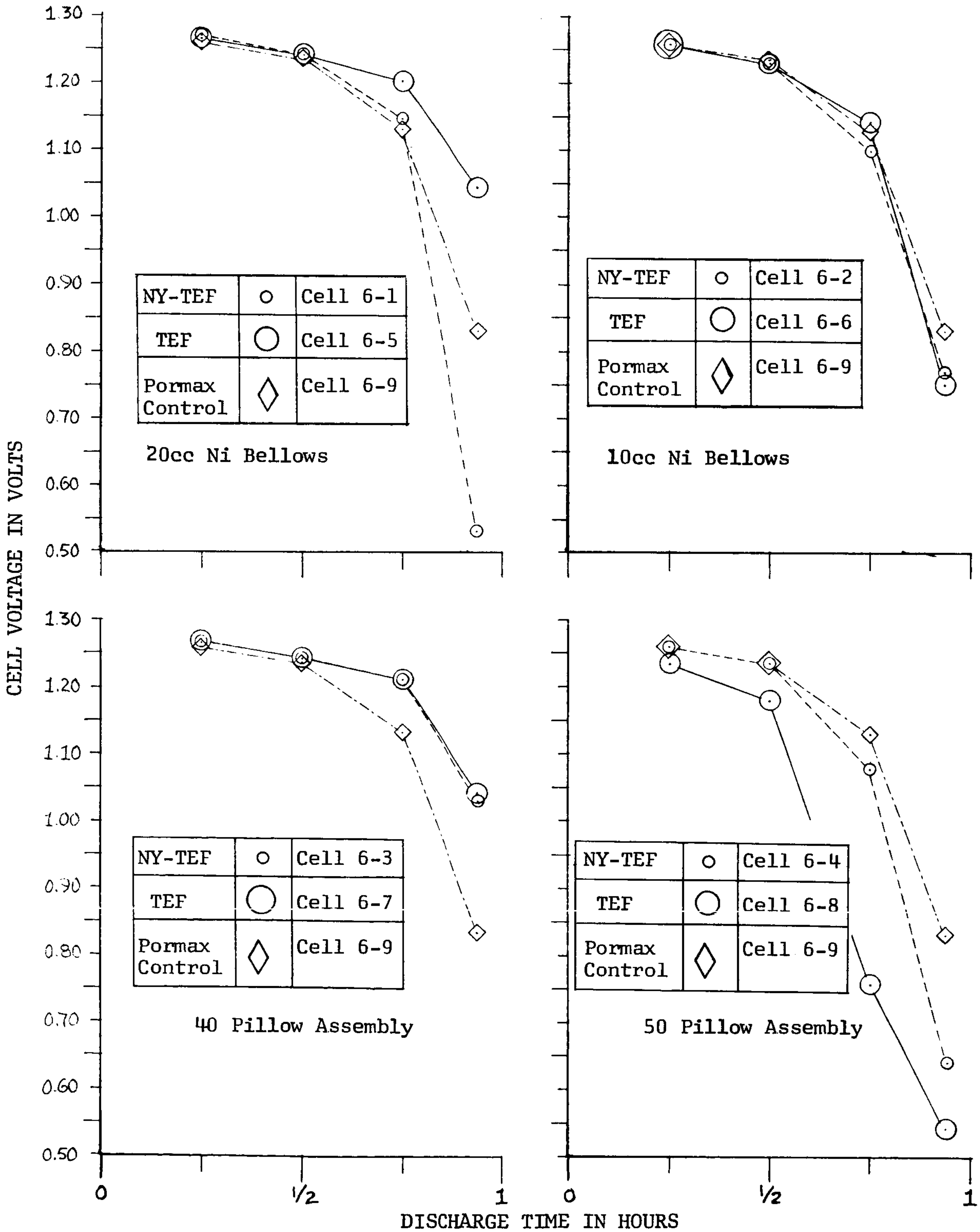


FIGURE 20

BELLOWS ACTION DURING 8-HOUR CYCLING
OF 6 AH NICKEL CADMIUM CELLS AT 0°C

Orbit Regime:
Charge = 7 Hrs. @ C/7
Disch. = 1 Hr. to 0.5C

Cell No.	Separator	Bellows	Fill Level	Oxygen Electrode	Seal	V	PSIA	Percent Level
6-3	NY-TEF	45 Pillows	67%	Yes	Evac. to Flood	○ (small)	--△--	--×--
6-7	TEF	45 Pillows	33%	Yes	Evac. to Flood	◯ (large)	—▽—	—●—
6-11	NY	40 Pillows	50%	Yes	Evac. to Flood	○ (small)	--△--	--×--
6-15	NY+FIL	20 CC Metal	50%	Yes	Evac. to Flood	◯ (large)	—▽—	—●—

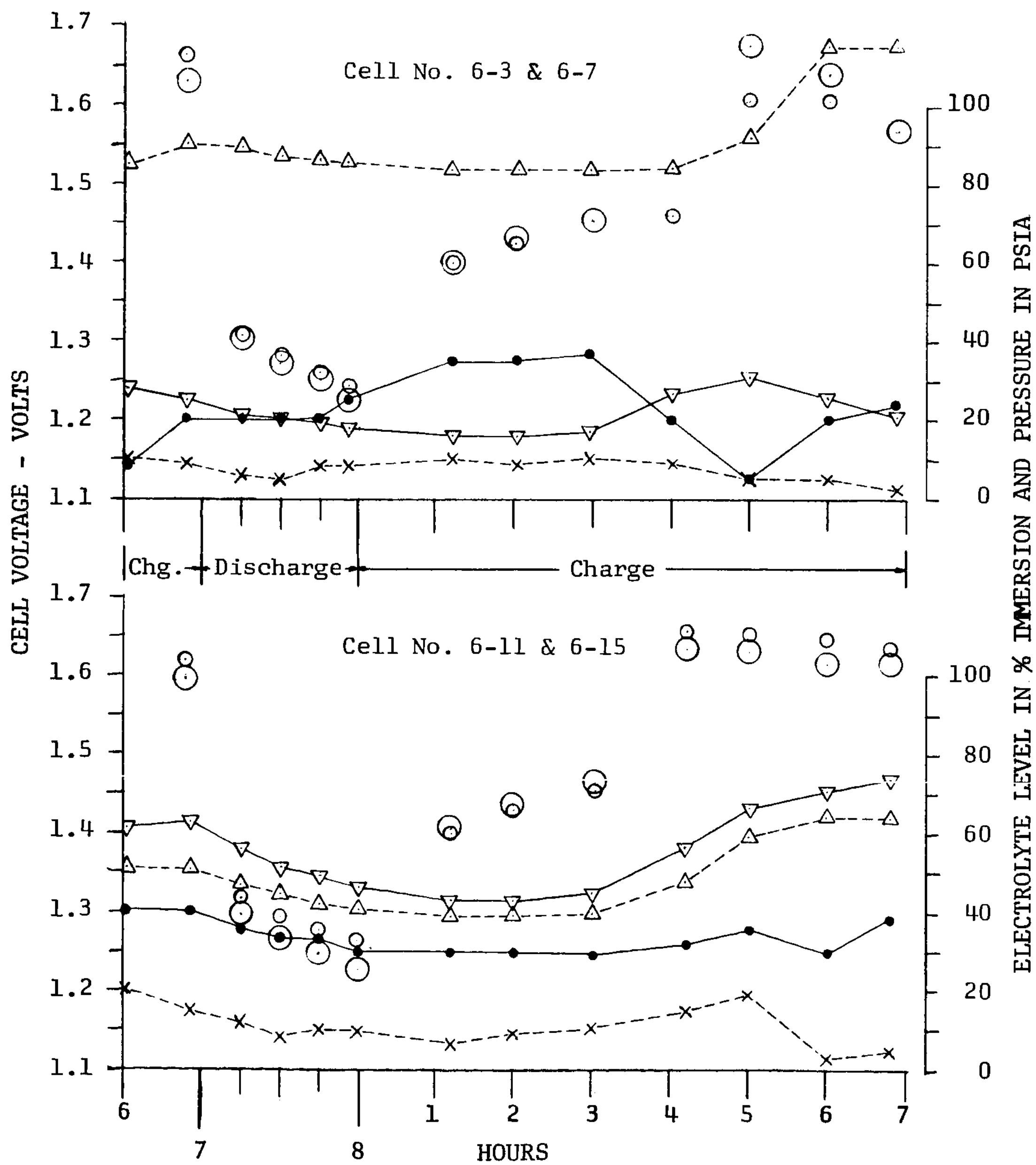


FIGURE 21

BELLOWS ACTION DURING 8-HOUR CYCLING
OF 6 AH NICKEL CADMIUM CELLS AT 40°C SHOWING EFFECT
OF TRAPPED GAS-BUBBLE DISLODGEMENT

Cell No.	Separator	Bellows	Fill Level	Oxygen Electrode	Seal	V	PSIA	Percent Level
6-3	NY-TEF	45 Pillows	67%	Yes	Evac. to Flood	○	---△---	--×--
6-7	TEF	45 Pillows	33%	Yes	Evac. to Flood	◯	—▽—	—●—
6-11	NY	40 Pillows	50%	Yes	Evac. to Flood	○	---△---	--×--
6-15	NY+FIL	20 CC Metal	50%	Yes	Evac. to Flood	◯	—▽—	—●-

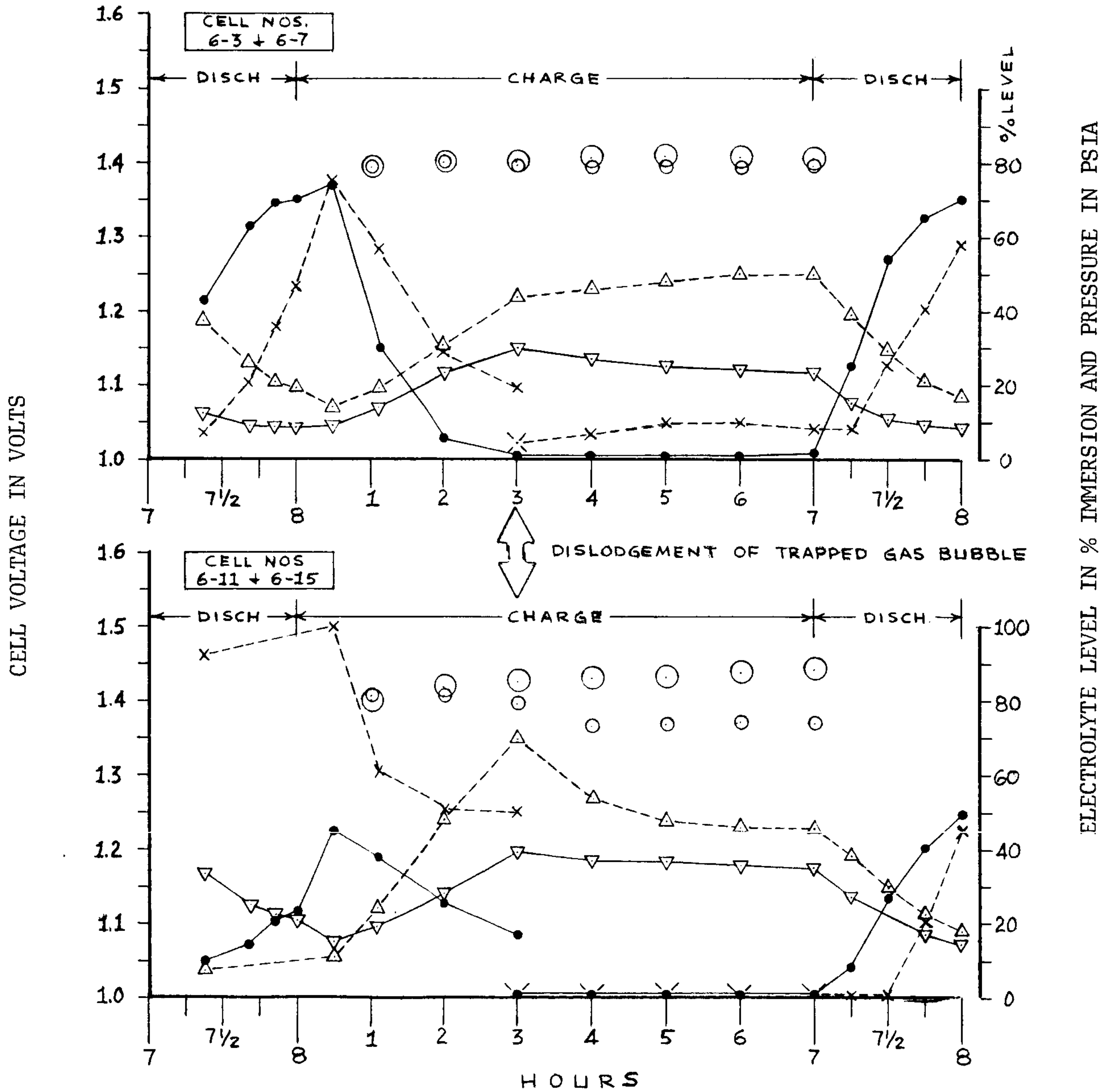
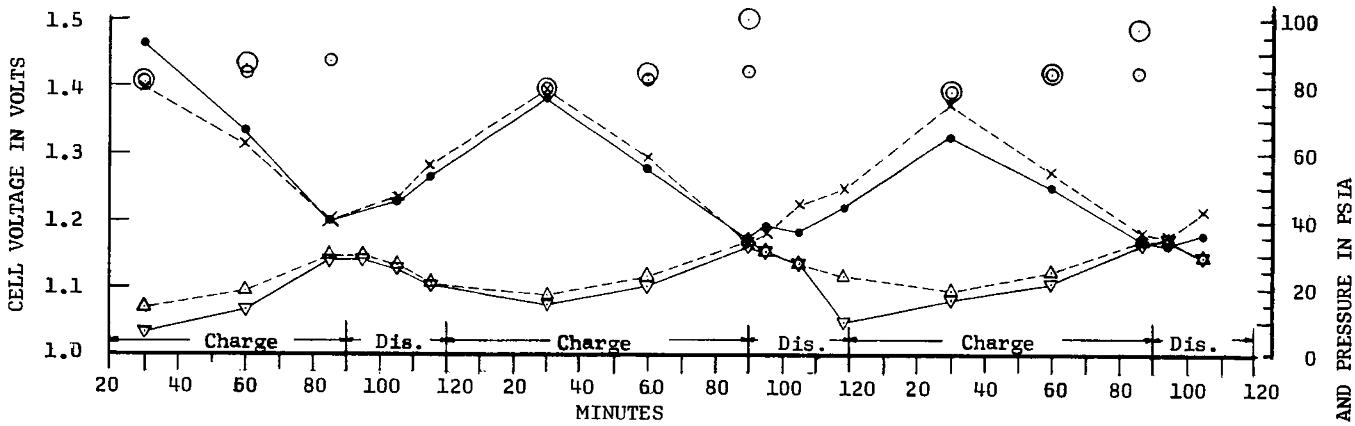


FIGURE 22

BELLOWS ACTION DURING 2-HOUR ORBIT CYCLING OF
6 AH Ni-Cd CELLS AT ROOM TEMPERATURE

<u>Orbit Regime</u>: Charge 90 Minutes @ 3.1 Amps.
Discharge 30 Minutes @ 8.5 Amps.

Cell No.	Separator	Bellows	Fill Level	O_2 Elect.	Seal	V	Press.	Percent Level
6-1	NY-TEF	20 CC Metal	67%	Yes	Evac. to Flood	○ (small)	---△---	---X---
6-2	NY-TEF	10M + 10P	50%	Yes	Evac. to Flood	◯ (large)	—▽—	—●—



Cell No.	Separator	Bellows	Fill Level	O_2 Elect.	Seal	V	Press.	Percent Level
6-3	NY-TEF	45 Pillows	67%	Yes	Evac. to Flood	○ (small)	----△----	---X---
6-4	NY-TEF	50 Pillows	67%	Yes	Evac. to Flood	◯ (large)	—▽—	—●—
6-9 Control	Pormax	None	Limited	Yes	Evac. to Flood	◊	-·-□-·-	None

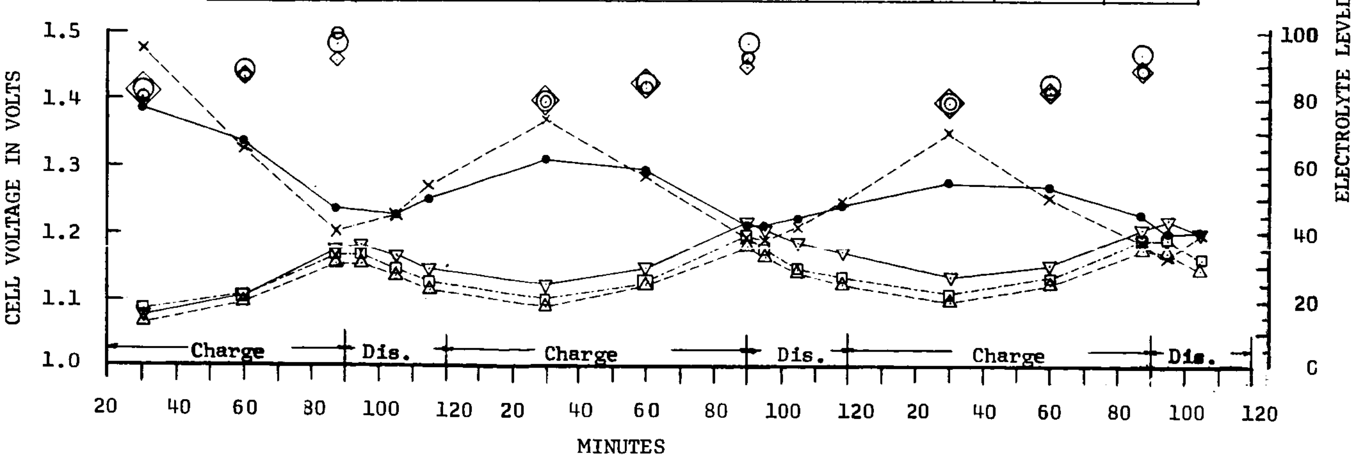


FIGURE 23

DISCHARGE CHARACTERISTICS OF SEALED
6AH SINTERED Ni-Cd CELLS WITH BELLOWS
DURING 2-HOUR ORBIT CYCLING

Orbit Regime: Charge 90 Minutes @ 3.1 Amps.
Discharge 30 Minutes @ 8.5 Amps.

Temperature: 25°C

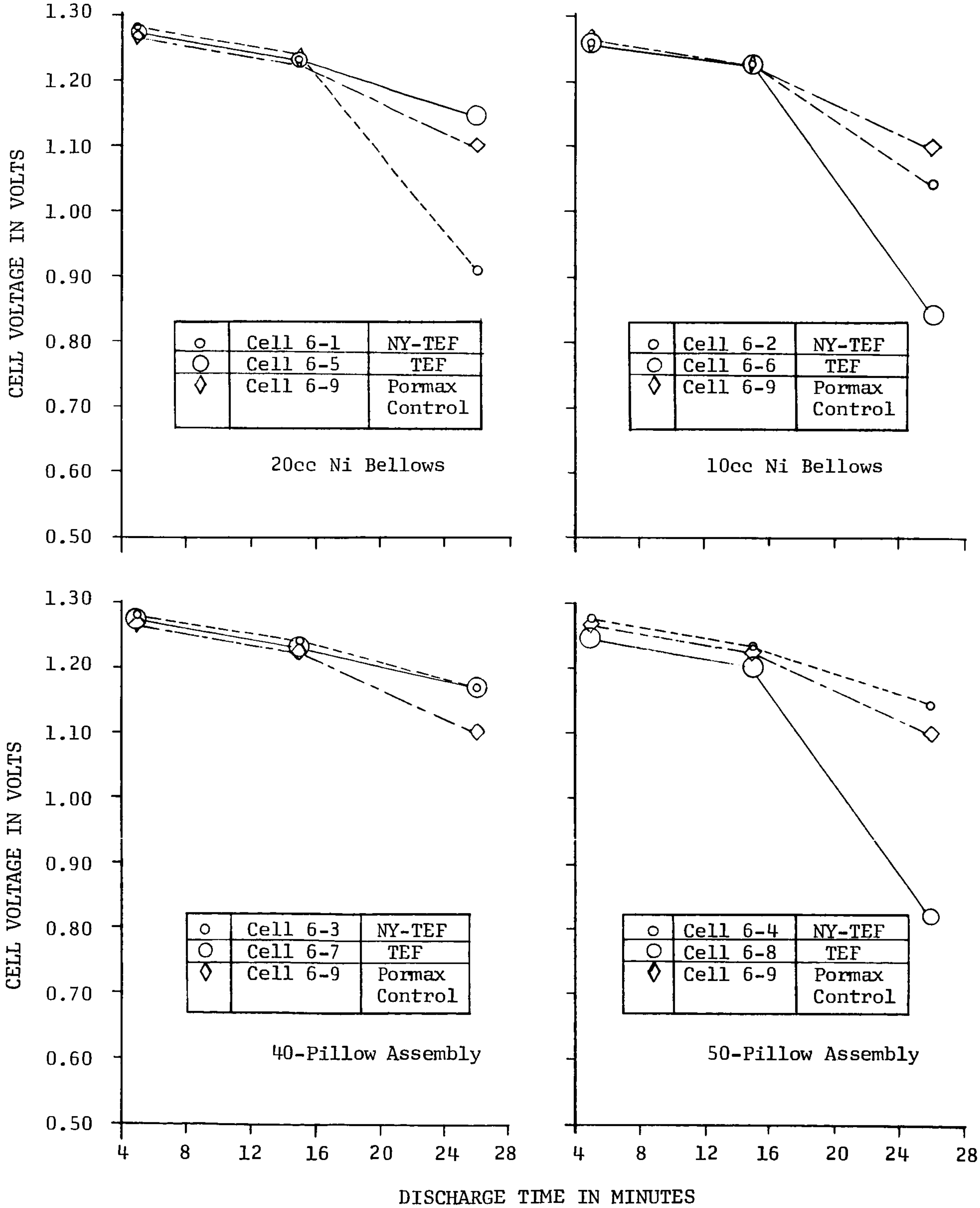


FIGURE 24

CELL ASSEMBLY FOR 8 AH SEALED
SILVER CADMIUM CELL WITH BELLOWS

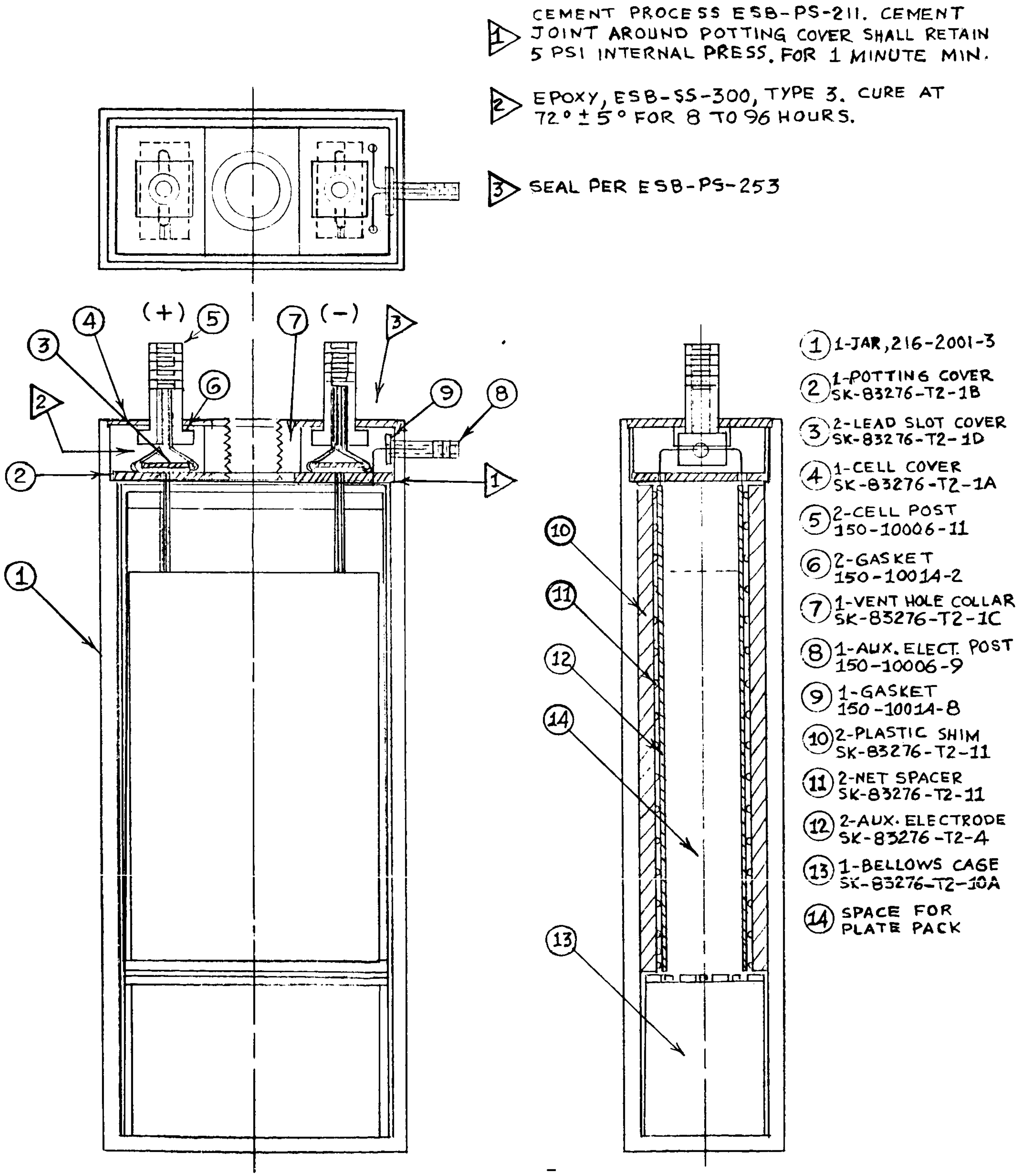


FIGURE 25

BELLOWS ACTION OF 30 PILLOWS DURING
24-HOUR ROOM TEMPERATURE CYCLING OF 8 AH
SEALED SILVER CADMIUM CELLS WITH 5 LAYERS OF
BORDEN C-3 SEPARATOR MATERIAL ON POS. AND NEG. PLATES

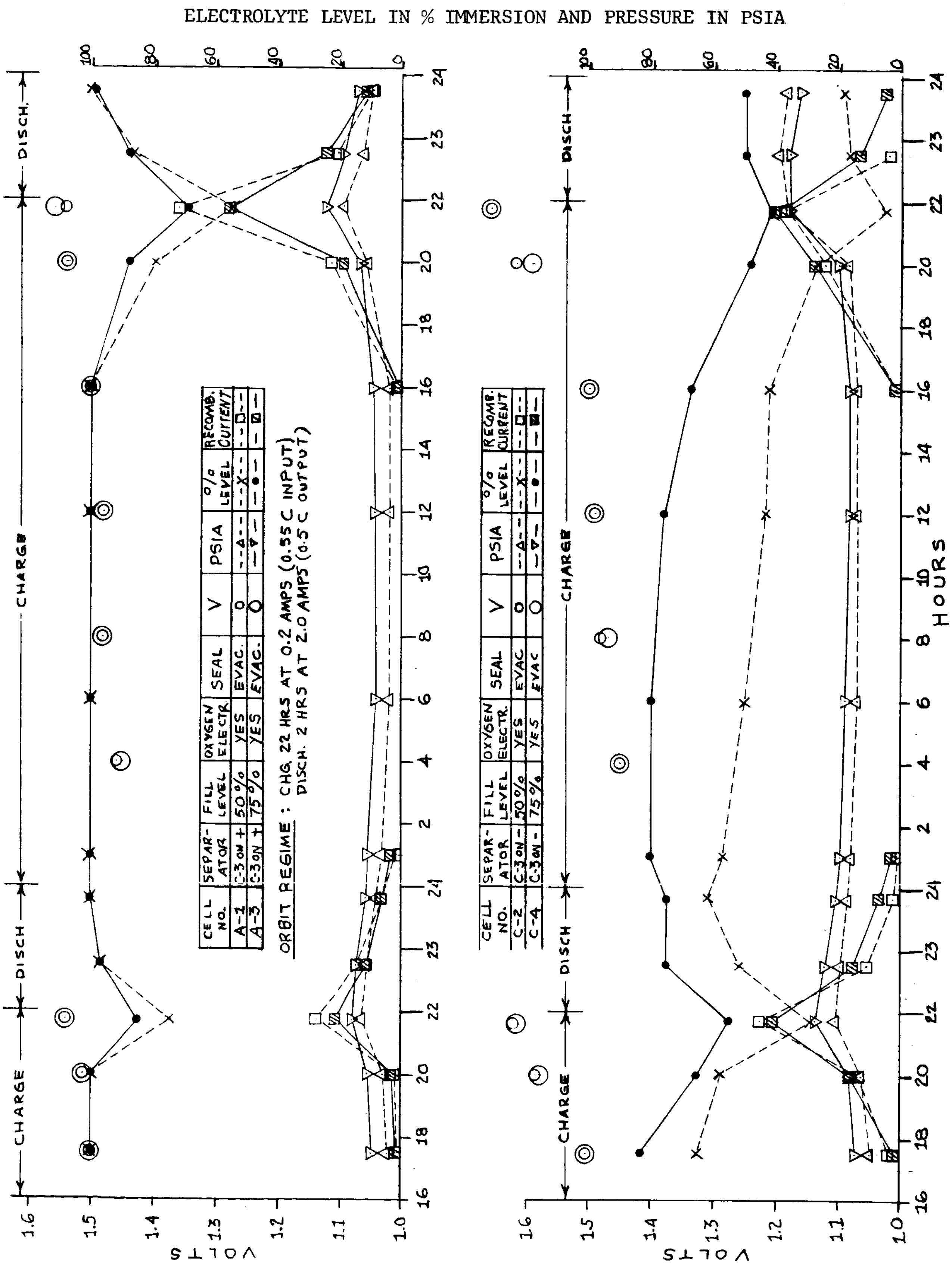
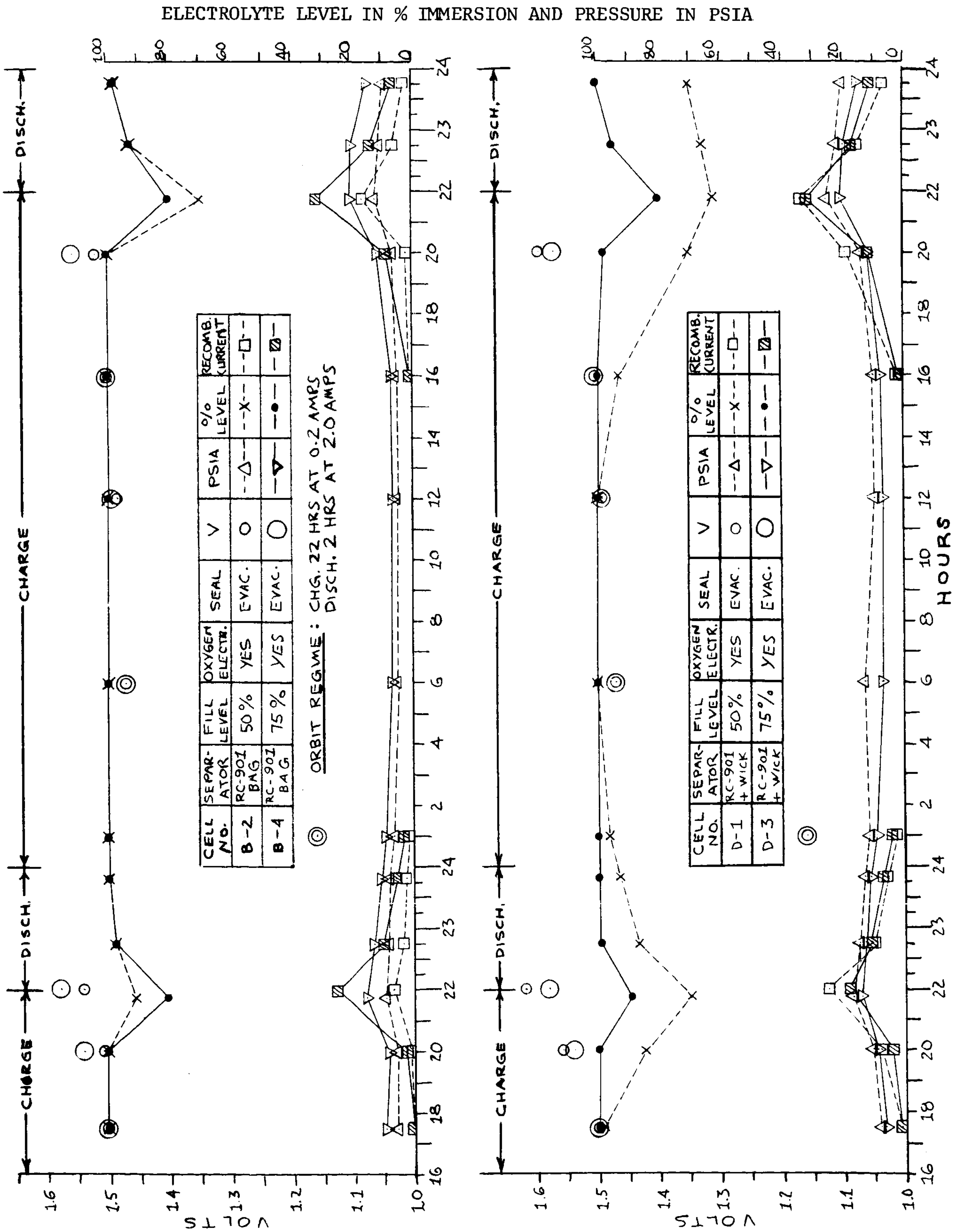


FIGURE 26

BELLOWS ACTION OF 30 PILLOWS DURING 24-HOUR
ROOM TEMPERATURE CYCLING OF 8 AH SEALED SILVER
CADMIUM CELLS WITH RC-901 SEPARATOR BAGS WITH AND WITHOUT WICK



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ESB Report No. E-13-66

FIGURE 27

BELLOWS ACTION OF 30 PILLOWS DURING 24-HOUR ROOM TEMPERATURE CYCLING OF 8 AH SEALED SILVER CADMIUM CELLS WITH 5 LAYERS BORDEN C-3 SEPARATOR MATERIAL AFTER 2nd OXYGEN TREATMENT

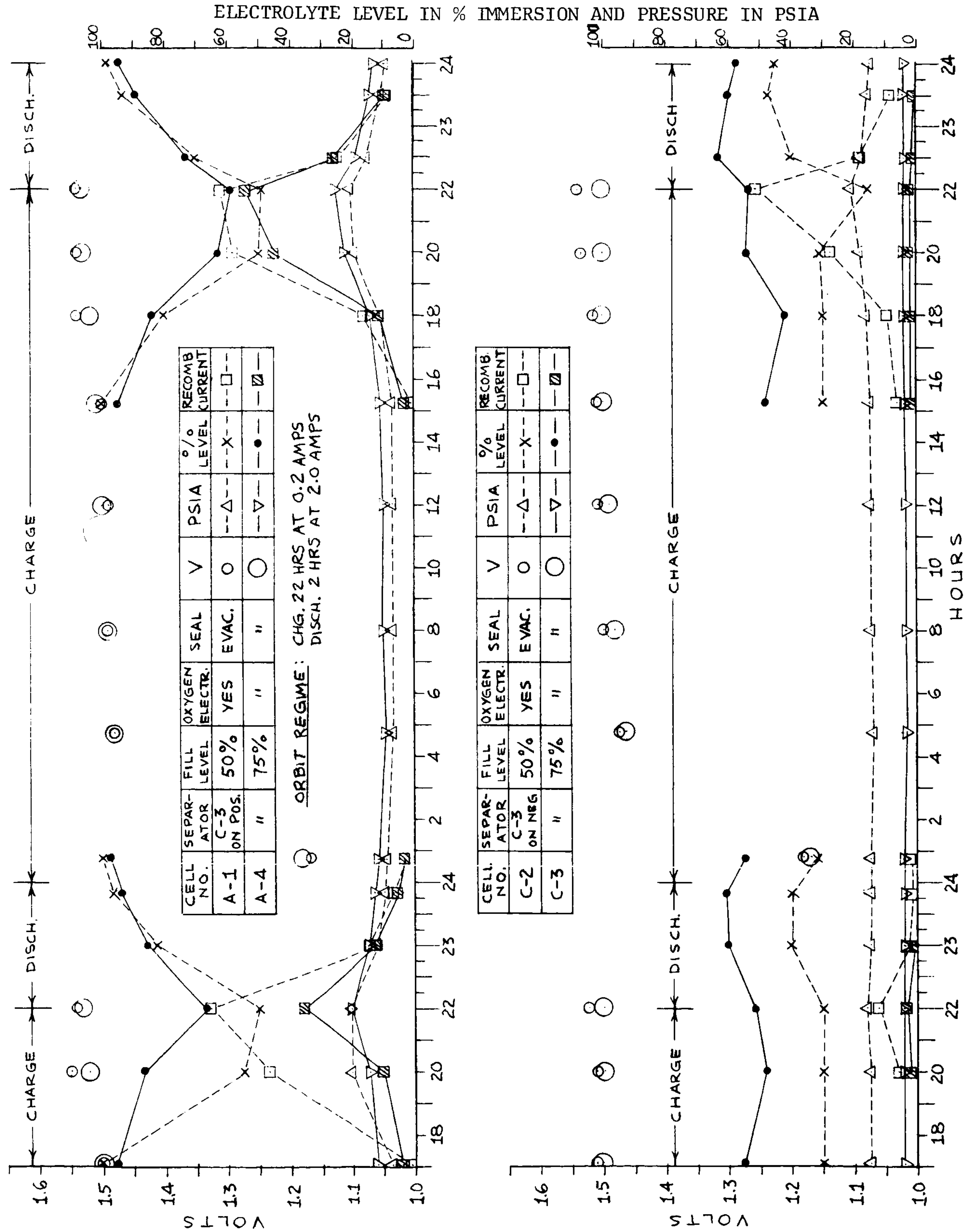


FIGURE 28

BELLOWS ACTION OF 30 PILLOWS DURING 24 HOUR ROOM TEMPERATURE CYCLING OF 8 AH SEALED SILVER CADMIUM CELLS WITH RC-901 SEPARATOR BAGS AND AFTER 2nd. OXYGEN TREATMENT

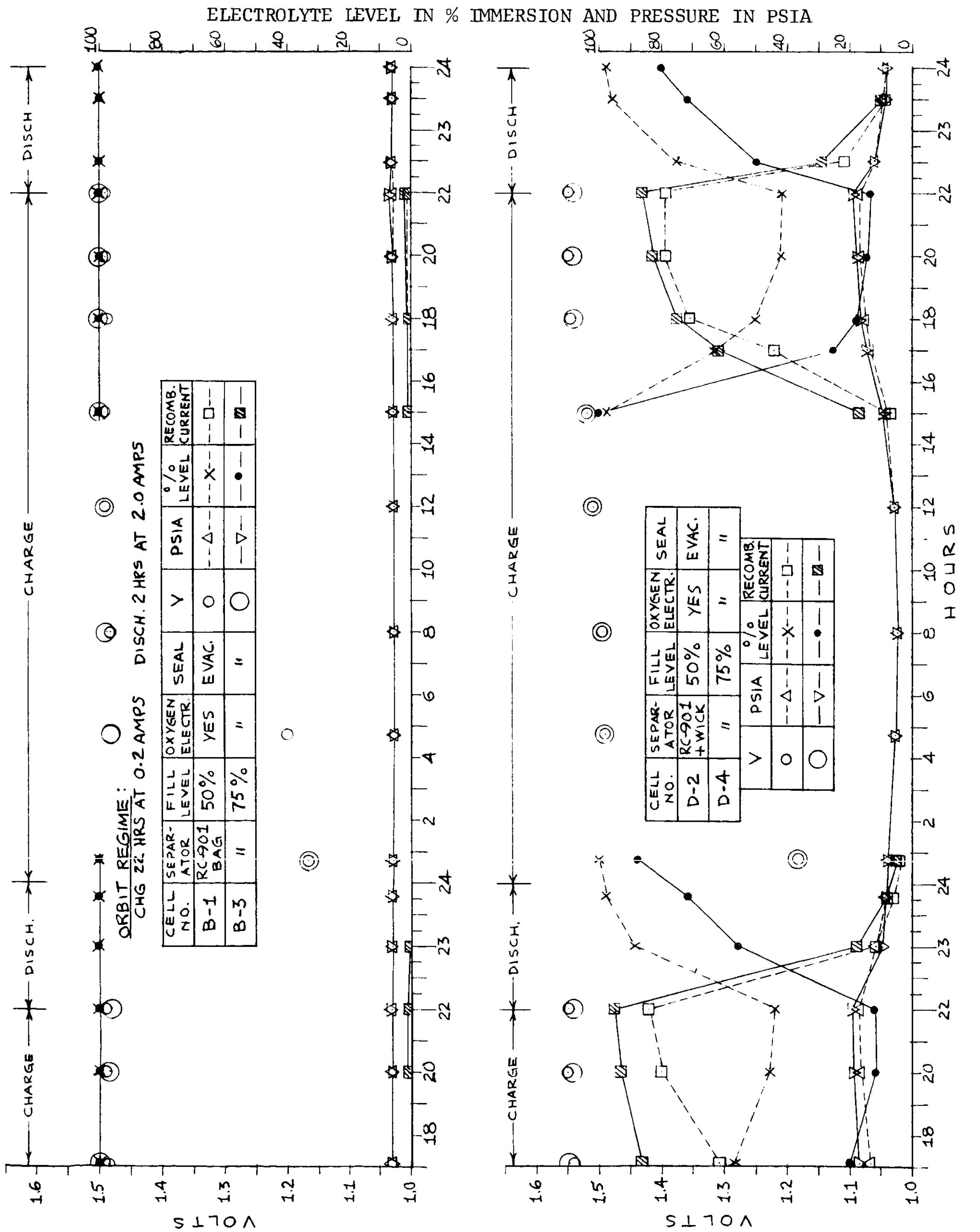


FIGURE 29

PERFORMANCE OF CONTROL CELLS DURING 8-HOUR ORBIT ROOM TEMPERATURE CYCLING OF 8 AH SEALED SILVER CADMIUM CELLS WITH NO BELLOWS AND 4 DIFFERENT SEPARATOR SYSTEMS

ORBIT REGIME: DISCH. 1 HR AT 4 AMPS
CHARGE 7 HRS AT 0.7 AMPS WITH 1.53 V/CELL LIMIT

CELL NO.	SEPARATOR	FILL LEVEL	OXYGEN ELECTR.	SEAL	V	PSIA	% LEVEL	RECOMB. CURRENT
A-5	5L C-3 ON POS.	50%	YES	EVAC.	o	--Δ--	--X--	--□--
C-5	5L C-3 ON NEG.	50%	YES	EVAC.	O	—▽—	—●—	—▨—
B-5	RC 901 POS. BAG	50%	YES	EVAC.	o	--Δ--	--X--	--□--
D-5	SAME + WICK	50%	YES	EVAC.	O	—▽—	—●—	—▨—

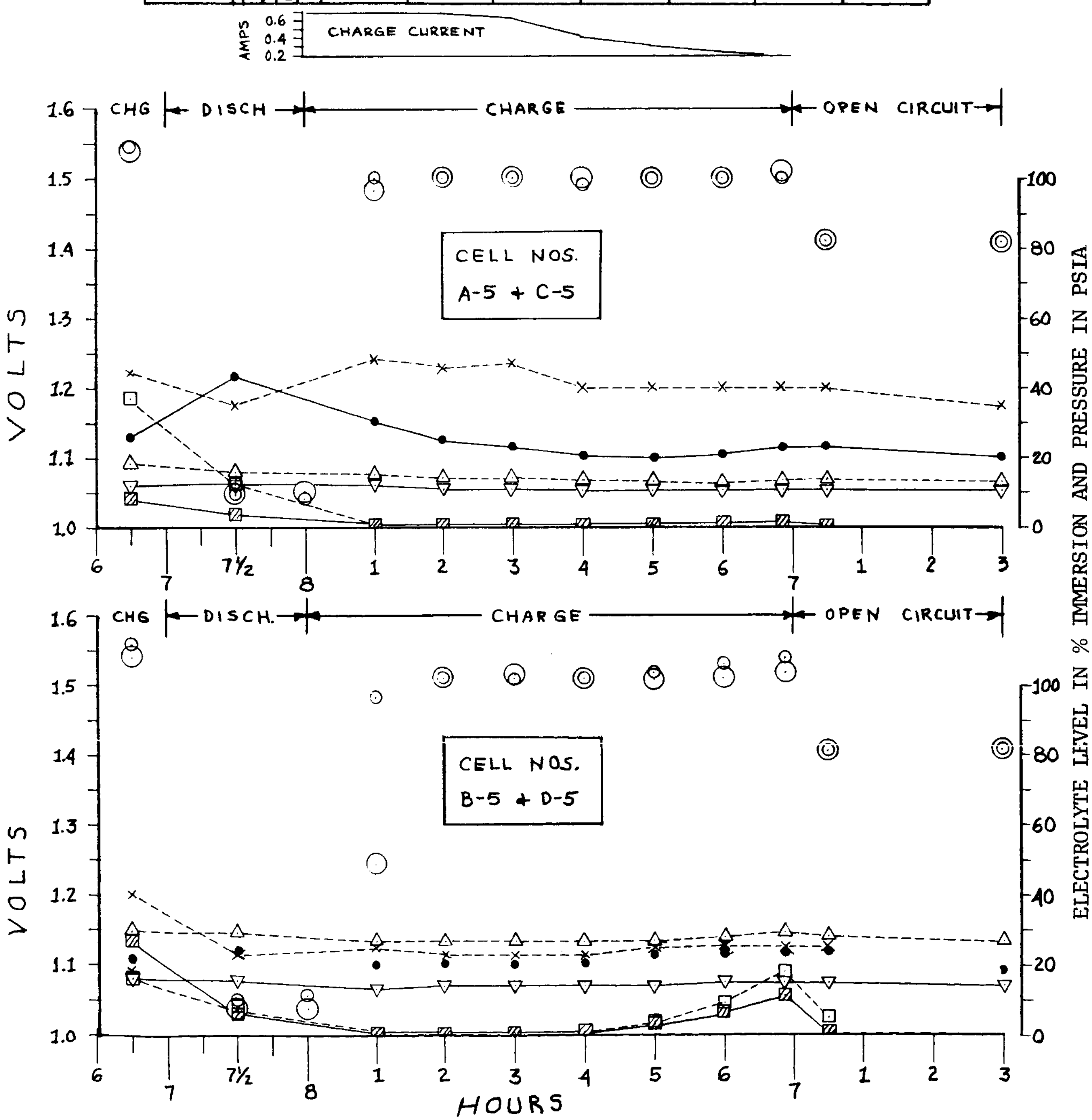


FIGURE 30

BELLOWS ACTION OF 30 PILLOWS DURING 8-HOUR ORBIT ROOM TEMPERATURE CYCLING OF 8 AH SEALED SILVER CADMIUM CELLS WITH PROPRIETARY RC 901 SEPARATOR MATERIAL AND EM-476 WICK

ORBIT REGIME : DISCH. 1 HR. AT 4 AMPS.
CHARGE 7 HRS AT 0.7 AMPS WITH 1.53 V/CELL LIMIT

CELL NO.	SEPARATOR	FILL LEVEL	OXYGEN ELECTR	SEAL	V	PSIA	% LEVEL	RECOMB. CURRENT
D-1	RC901 + WICK	50%	YES	EVAC	o	--Δ--	--x--	--□--
D-2	RC901 + WICK	50%	YES	EVAC	o	--Δ--	--x--	--□--
D-3	RC 901 + WICK	75%	YES	EVAC	○	—▽—	—•—	—▨—
D-4	RC 901 + WICK	75%	YES	EVAC	○	- ▽	—•—	—▨—

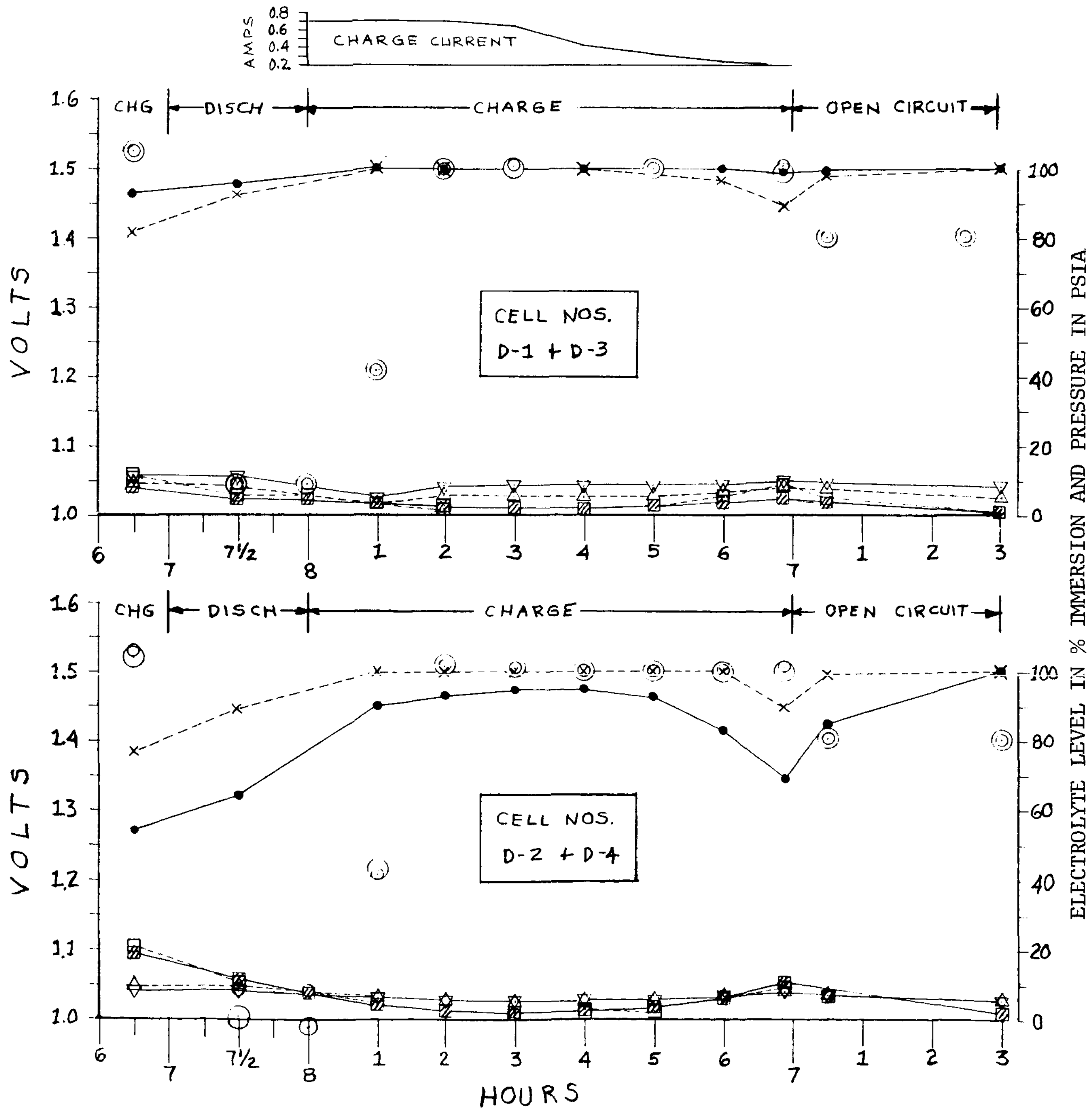
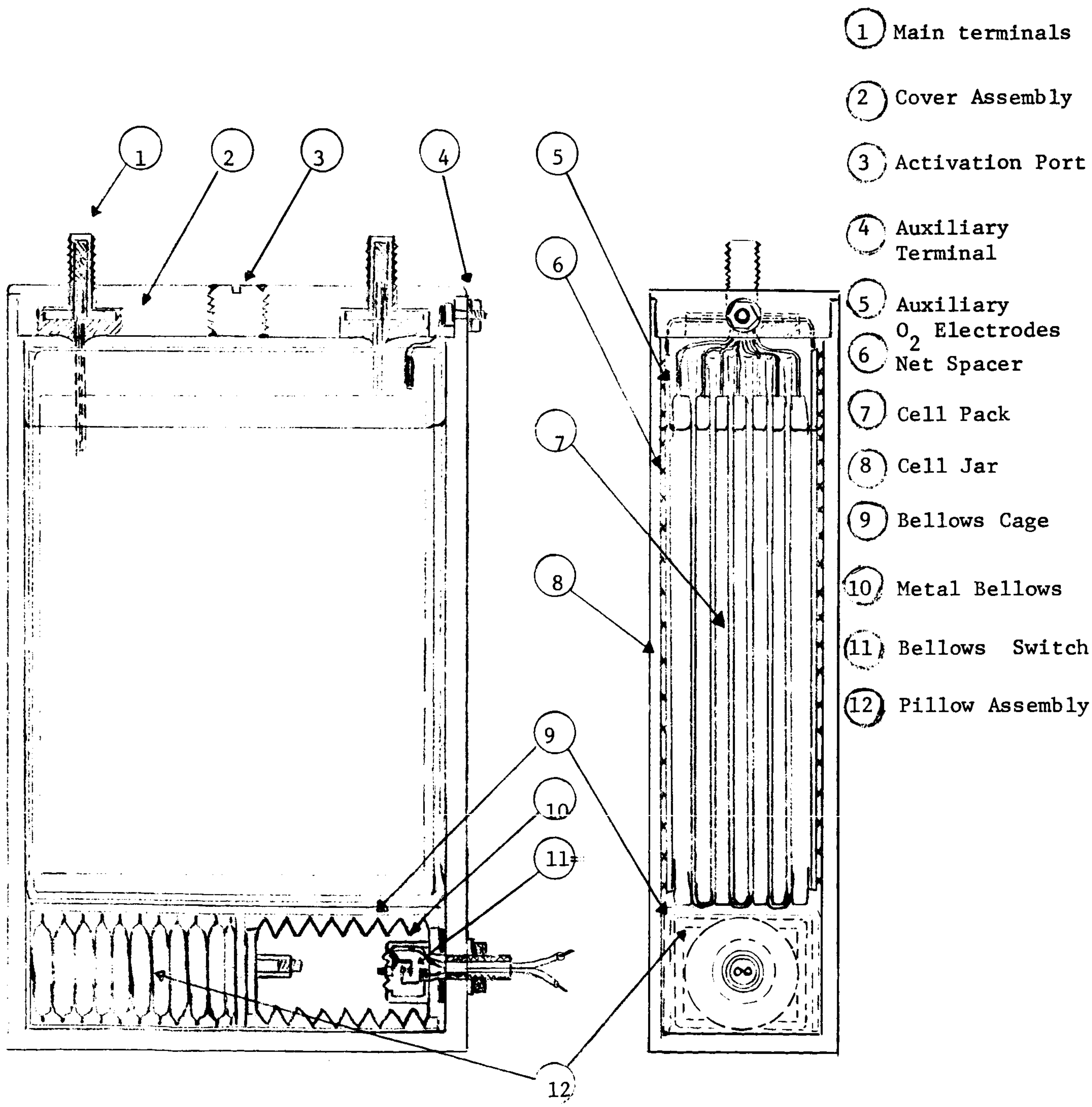


FIGURE 31

SEALED 100 A.H. Ag-Cd CELL WITH BELLOWS SWITCH ASSEMBLY FOR TERMINATING CHARGE



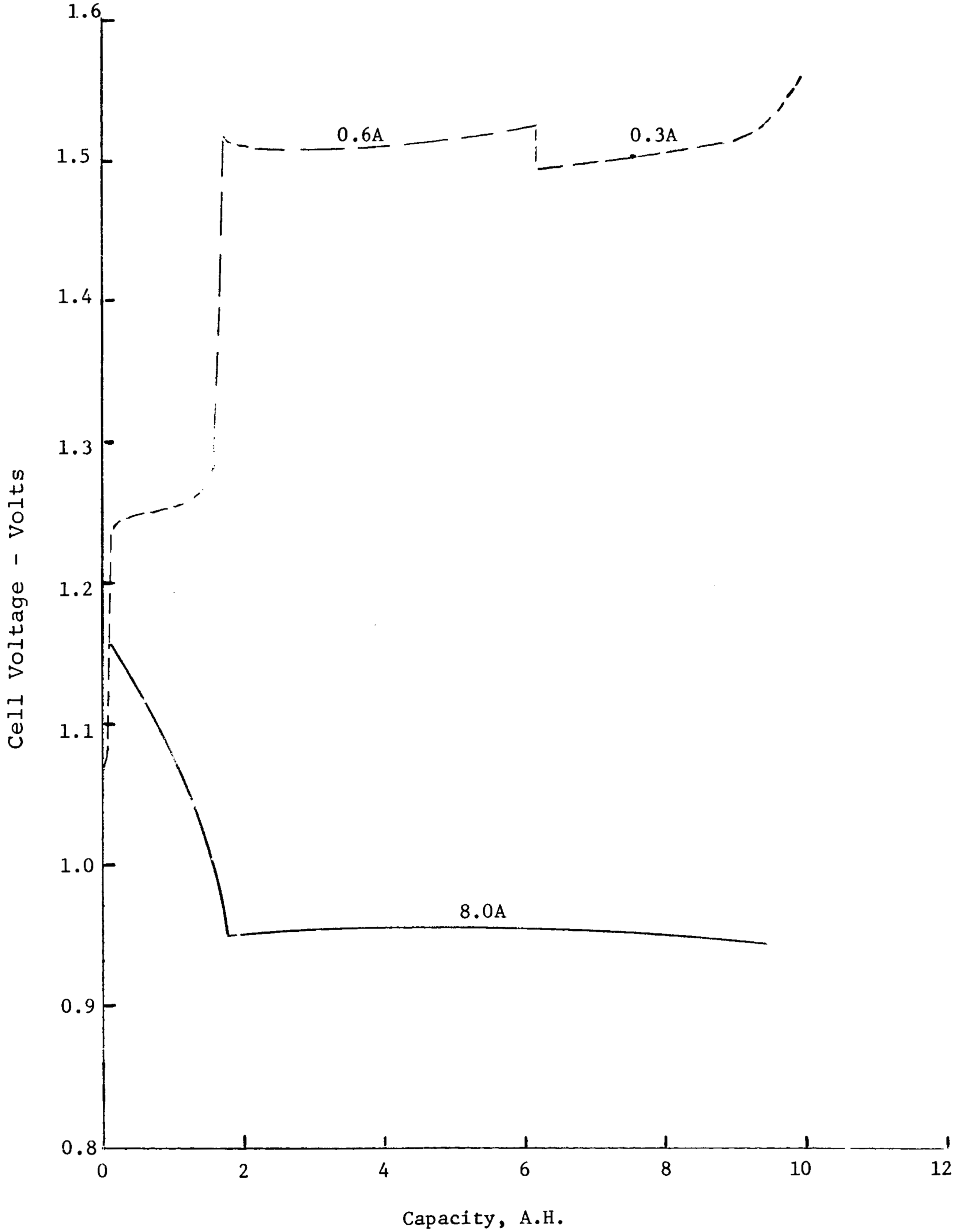


FIGURE 32

FORMATION DISCHARGE AND RECHARGE OF
SEALED 8 A.H. Ag-Cd CELL WITH BELLOWS DEVICE

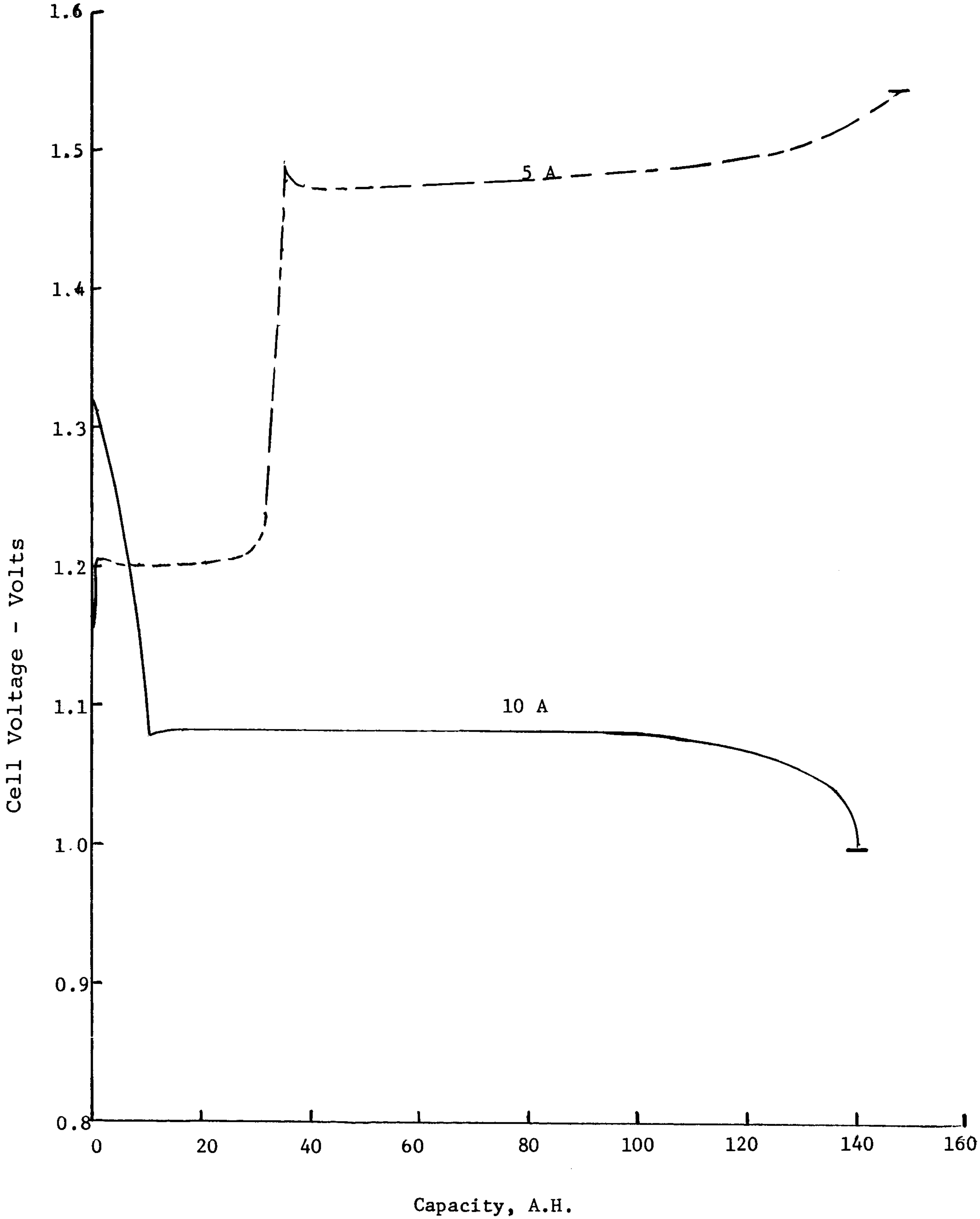


FIGURE 33

FORMATION DISCHARGE AND RECHARGE OF SEALED
100 A.H. Ag-Cd CELL WITH BELLOWS-SWITCH DEVICE